# IMPACT

## *of science on society*

THE UNIVERSITY OF MICHIGAN
AUG 29
PERIO
READ

Vol. X (1960), No 2

SPECIAL ISSUE ON MARINE SCIENCES

Man discovers the Sea — by H. ROTSCHI

Marine Optics — by Y. LE GRAND

Hydropsis: its Scientific Background and Application in Navigation, Fisheries and Meteorology — by T. LAEVASTU

The Influence of Sea-floor Contours on Structural Engineering in Coastal Waters — by A. G. DE ROUVILLE

IMPACT *of Science on Society*
quarterly

Annual subscription:
[A] $1.75; 9/6 (stg.); 4,50 NF
Per copy:
[A] $0.50; 2/6 (stg.); 1,25 NF

Any of the National Distributors listed at the end of this number will accept subscriptions; rates in currencies other than the above will be supplied on application to the National Distributor in the country concerned. When notifying change of address please enclose last wrapper or envelope.

The articles appearing in *Impact* express the views of their authors, and not necessarily those of Unesco.

Printed in France by Berger-Levrault, Paris.
© Unesco 1960 NS.60/I.35/A

UNITED NATIONS EDUCATIONAL, SCIENTIFIC
AND CULTURAL ORGANIZATION
Place de Fontenoy, Paris-7e (France)

# Contents

IMPACT, Vol. X (1960), No. 2

Introduction . . . . . 77

MAN DISCOVERS THE SEA
by H. ROTSCHI . . . . . 79

*This article, which describes some of the ways in which the sciences of the sea have influenced the development of society, is in three parts. In the first part, the author briefly retraces the steps in mankind's discovery of the world's seas and shows how and why what was at first a purely empirical approach gradually developed into a scientific study. In the second part he discusses the principal human activities in which the sea today plays an important part and which have benefited appreciably from the growth of oceanographic science. The third part gives a brief outline of the prospects for the future: as the industrial and domestic demands for raw materials and energy grow, the resources of the land areas will gradually be exhausted and man will be forced to turn to the sea which is the Earth's greatest storehouse of foodstuffs, of industrial raw materials and of power.*

MARINE OPTICS
by Y. LE GRAND . . . . . 104

*The problem of the penetration of the water of the sea by solar radiation is one that is important, not only to the physicis but to the biologist as well. For it is through the process of photo synthesis that the productivity of organic matter in the sea, on which marine life so largely depends, is ensured. Since these underwater regions, still so little known, may one day constitute the main reserves of food for mankind, it is well that we should have the fullest possible understanding of the optical phenomena peculiar to them. Research in marine optics has already proved a powerful aid to the study of ocean water and the sea floor.*

HYDROPSIS: ITS SCIENTIFIC BACKGROUND AND APPLICATION IN NAVIGATION, FISHERIES AND METEOROLOGY
by T. LAEVASTU . . . . . 121

*Human activities on the sea and its shores require an ability to predict oceanic features such as water temperature, currents and waves. While some prediction systems have already been developed, a more comprehensive programme of routine observation of 'key' elements and processes is needed. The author discusses how such a programme will be developed and used for the benefit of navigation, fisheries and other marine occupations.*

THE INFLUENCE OF SEA-FLOOR CONTOURS ON STRUCTURAL ENGINEERING IN COASTAL WATERS
by A. G. DE ROUVILLE . . . . . 131

*The author of this article advocates a more scientific approach—possible in the light of recent developments—to the study of engineering works exposed to a heavy swell, such as dikes or coastal protection works, so that the stresses to which they may be subjected can be deduced from a more detailed knowledge of the contours of the ocean floor off the coast. The convergence or divergence of the perpendiculars to the contour lines indicates a strengthening or a reduction of the swell in certain directions. The slope and constitution of the embankments of the works, or the extent to which the vertical walls of other types of structure is submerged by the water, are also factors that should not be overlooked. He then discusses the social importance of such studies, firstly for providing new countries with the ports they lack, properly adapted to their needs, and, second, for protecting and maintaining coasts and beaches.*

## CONTENTS OF PRECEDING ISSUES

Vol. IX (1959), No. 3

Grafting for Productivity in Plants and Animals, by PIERRE BOITEAU.
The Development of Optics and its Impact on Society, by VASCO RONCHI.
Teaching the History of Science, by RENÉ TATON.
Current Problems and the 1959-65 Seven-Year Plan in the USSR, by NORAJR SISSAKIAN.
The International Conference on Scientific Information, by PAUL BOQUET.

Vol. IX (1959), No. 4

How Life on Earth began, by A. I. OPARIN.
The Place of Laboratory Animals in the Scientific Life of a Country, by W. LANE-PETTER.
The Place of Operational Research in the Development of Modern Society, by J. LESOURNE.
Science in Modern India, by Dr. A. RANGANANTHAN.
Problems of Waste Disposal in the Wide-scale Use of Radio-isotopes, by W. G. MARLEY.

Vol. X (1960), No. 1

Computers and Automation, by E. L. HARDER.
Machine Translation and the Human Being, by D. J. PANOV.
Machine Translation of Languages: Research and Organizational Problems, by E. DELAVENAY.
The Scientific Attitude: A Possible Misunderstanding, by P. AUGER.
International Conference on Information Processing, by S. DE PICCIOTTO.

# Introduction

Whilst men are making tremendous efforts to enter outer space, they have also become more acutely aware that there is still much to learn about the planet on which the majority of them will live out their lives. And this awareness is especially acute in relation to those parts of the earth that are covered by seas. Tremendous interest in the sea has been generated in recent years by accounts in certain books (for example, Rachel Carson's *The Sea around us* by reports of certain discoveries (for example, of the Coelacanth), and by the revelations following from certain technological developments (for example, the bathyscaphe and the aqualung). This growth in interest has been in part a cause—as well as being a result—of increased oceanographic research activity in recent years: several nations have already greatly expanded their programmes of oceanographic research and others have announced their intention of doing so. With this growth of national activity there has been a growth of international exchanges in this field. Within the past decade several international bodies concerned with fisheries have greatly increased their efforts to co-ordinate their member nations' research programmes on the sea; and some highly successful joint research projects have been completed. The International Geographical Year (IGY) further demonstrated both how, and with what great benefits, such co-operation could be developed. It is a direct result of these successes, and of various forces demanding better knowledge of the sea that simultaneously with the laying of plans for more oceanographic research others are being prepared for more international action in this field. It must be added that in truth many of the things that need to be known about the sea are such that they could be discovered, within a reasonable time, only by co-operative international action of the kinds proposed.

Increased knowledge of nature may be sought for itself, and does not need justification, but where a need exists to control nature in the way that knowledge makes possible, and where the kind of knowledge required can be specified, it is proper to organize research with these ends in view.

At the present time many proposals are current for international action in the field of the marine sciences, and in the face of the pressure to intensify and extend oceanographic research it is necessary to consider the kinds of information required; the means by which they can be obtained; and then to consider and to put into train various kinds of international action that would assist in the achievement of these aims.

For this purpose Unesco is convening, with the assistance of FAO, an intergovernmental conference on research in marine sciences. As a contribution to this broad effort a special issue of *Impact* has been prepared to present a general review of the subject field. The articles of this issue have the common task of describing, in each of a series of special sections; (a) how oceanographic knowledge enables man to make best use of the sea and to cope with its forces; (b) how knowledge of the sea is acquired; (c) the effect on society that advances in oceanographic research are likely to have.

Man's interest in the sea relates to its mineral, fishery and energy resources; its importance for transport and communications; its effect on harbours and foreshores and man's works there; its role in weather. His understanding of these matters is acquired by his study of the physical, chemical and biological features and processes of the sea. For the specialist, oceanography may be presented by way either of the series of matters of interest or of the principal lines of study—that is, physical oceanography, chemical oceanography, marine geology, marine biology, etc.

The articles in this special issue, however, neither describe what is known of the resources and other features of the sea, nor give accounts of lines of oceanographic research. Their purpose is quite otherwise, namely, to describe how oceanographic information is obtained and assembled (and more particularly how it is *used*), to indicate some of the lines along which oceanographic research is likely to proceed in the near future, and to suggest some of the effects that successful prosecution of this research may have on society.

The approaches adopted by the several authors vary. The first article recounts the history of oceanographic research, and establishes a background against which to appreciate the prospects, set out in other articles, of future progress. The next describes briefly the study of the ocean floor and the use made of the results obtained. Studies of life in the seas and the use made in fisheries of the results of these studies are the subject of the third article.

# MAN DISCOVERS THE SEA [1]

## The Influence of the Sea on the Growth of Human Societies

*by*

H. ROTSCHI

*H. Rotschi is in charge of the Physical Oceanography Section of the Institut Français d'Océanie (Noumea, New Caledonia). He took part in the Capricorn expedition organized in 1952-53 by the Scripps Institution of Oceanography of the University of California. He is also a member of the Physical Oceanography Section of the Comité National Français de Géodésie et Géophysique.*

### MAN'S DISCOVERY OF THE SEA

*Ocean exploration down to the nineteenth century*

At the dawn of civilization, as far back as the earliest knowledge we possess of the science of our ancestors, the ocean 'girdling the earth with its endless stream' was looked upon as a circular river running round the edges of the world like the rim of a wheel; and to cross it was a homeric adventure to be attempted only by men of exceptional courage or lust for gain.

Long before anything of the kind was tried, generation after generation of traders, had—probably for many centuries—been making their way in fragile vessels propelled by oars, equipped with primitive sails but without rudders, along the coastal waters of the lands which held in their interior all the treasures of that age—essences, spices, ivory, gold, silver, gums and precious woods. Two thousand years B.C.—long before the Trojan war—the Phoenicians, pioneers of international trade and ocean exploration, set up trading posts on the shores of the Red Sea and the Indian Ocean. In the Persian Gulf the first lighthouses appeared, served by a priestly caste responsible for maintaining the fires night and day; these lighthouses also served as mail offices and information centres for mariners in those days, collecting all information on routes followed, dangers met with, navigational techniques used, coastal topography, and winds and currents. Soon schools were founded which taught the art of navigation and of plotting a course from astronomical observations.

The real cradle of seafaring was the Mediterranean. It was there that the

1. When this article was written the author had not seen the article on oceanography by G. E. R. Deacon published in an earlier issue of *Impact* (vol. IX (1958), no. 2). He offers his apologies for any similarities between the two.

tremendous adventure started which led men out on to the high seas, spurred on at first purely by the desire for gain, but later by the thirst for knowledge for its own sake. The Phoenicians, swarming westwards through the Pillars of Hercules, turned south along the coast of Africa and north up the coasts of Europe as far as Britain until the cold, fog, high winds and their helplessness against the powerful tidal currents, unknown in the Mediterranean, caused them to turn back once more to the south.

This small-scale coastal traffic carried on by traders more mindful of their profits than of the advancement of geography was succeeded very soon by the era of long-distance ocean exploration started in 330 B.C. by Pytheas of Marseilles, geographer and astronomer, who sailed north as far as the Arctic Circle, turning back only when floating ice barred further progress. He seems to have sighted Britain, the Shetlands and Iceland or Norway. As to the fruits of his voyage, he brought back neither gold nor silver nor any merchandise, but a first report on the Arctic approaches and a precise astronomical explanation of the Midnight Sun, entitling him to rank as the first oceanographer. He it was, too, who first used astronomical calculations to plot the position of fixed points. The great ocean journeys of exploration captured the imagination of the learned throughout the Mediterranean and encouraged them to exercise their minds on all the aspects of geography perceptible by man in their day. Pythagoras deduced the spheroid form of the earth from the accounts of mariners and together with Herodotus, Aristotle, Hipparchus and Ptolemaeus, laid the foundations of what was later to become the science of oceanography as we know it today. Soundings were taken, charts plotted and the positions of harbours determined; distances traversed were calculated from the stars; and currents, winds and tides ceased to be terrifying manifestations of the wrath of heaven and became aids which men had learned to use to extend the ocean routes carrying the flow of trade and serving in turn as a vehicle for armies, ideas and wealth.

The greatest, strongest and most influential countries were those with the most and the largest harbours, equipped with the best facilities, and situated in the best places to attract the steady flow of trade which is the mainspring of all human activities; and the approaches to these ports were studded with carefully tended lights and guiding marks. Power came from the sea, by the sea, and did not exist apart from the sea.

The Pax Romana changed all this: conquest on land was preferred to ocean adventure, and the old primitive terrors and superstitious fears reasserted their hold over the heirs of the first explorers.

Those who kept the sacred fire alight were the Vikings and the Arabs. The Arabs gave the West the hinged rudder, the compass and the astrolabe, and once these technical improvements were in use the way was opened to long-distance navigation. Nevertheless it was without their help that the Vikings, in open wooden ships with a single square sail, explored the North

Sea, reached Gaul and southern Britain and then discovered in succession the west coasts of the British Isles, Iceland, and Greenland, to land finally in America.

A few centuries later Prince Henry the Navigator sent forth his caravels to open the route to the lands rich in spices and gold, and less than 100 years after that Vasco da Gama reached India. This gradual eastward thrust from the western countries was balanced by the more or less contemporaneous irruption into the Pacific of the Polynesians, trusting their lives to frail outrigger canoes and to their knowledge of the stars.

After that, once Christopher Columbus had shown the way to the Americas, there was a rush in search of new and hitherto unknown direct routes to Asia and in quest of the last continent still awaiting discovery, Antarctica, credited in the contemporary imagination with far more amenities than in fact it possesses. Balboa then discovered the Pacific; Magellan circumnavigated the world and made the first soundings of the ocean deeps, while Cook found a south polar ocean girdling the globe instead of the Antarctic continent he had expected, and traversed the Pacific from north to south and east to west. After him came Bougainville and a host of others, of whom many were sealers and whalers.

Finally came the search for the North-West Passage, where the great names are Davis, Hudson, Barents and Bering.

At the dawn of the nineteenth century the terrestrial globe—or most of it—was well known. All that remained to be done was to discover a few islands lost in the vastness of the ocean and to explore the Poles. But still nothing was known of the ocean deeps or of the nature or conformation of the bottom of the sea.

### *The geography of the seas and maritime reference sources*

After the four thousand years and more since the first man, driven by curiosity and the lust for gain, took to the sea, how did things stand? In his *Physical geography of the sea*, published in 1855, Lieutenant Maury of the American Navy epitomized the centuries' accumulated lore on winds and currents which he had been able to collect from the seafarers of all nations. By collating all the material given him, Maury was able to issue charts which enabled sea captains to change the routes of the long ocean passages and cut weeks off the sailing time, say, to Australia or round the Horn. These were the first *Sailing directions*, to this day the bedside book of every ship's captain and every navigating officer; they contain all that is known of the physical geography of the seas, coastal approaches, winds, currents and tides, hazards and seamarks; and without them many a ship would be lost by seeking to approach inhospitable coasts.

Obviously, much information had been put on paper before this by ships'

captains anxious to benefit by the lessons of experience. Unhappily, all these navigational aids, being, *ipso facto*, the keys to wealth and power, were the carefully guarded secrets of shipowners and masters.

The most ancient reference works which have come down to us are the portolani and peripli, and from them we can form some idea of the technical knowledge of mariners in the ancient world. The portolani were charts showing landing places on the Mediterranean coasts and were used in conjunction with the sailing directions then in force; the peripli, on the other hand, supplied all necessary details of coastlines, havens and supply facilities.

Next came more specifically marine charts. The earliest still extant date from the end of the sixteenth century and are confined almost entirely to the waters of Western Europe and the East Atlantic; but little by little geographical knowledge increased with a corresponding improvement in the accuracy and coverage of the charts publicly available. However, by far the best charts were those produced by the private companies—such as the Compagnie des Indes (East India Company)—which maintained their own hydrographers and had remarkable collections of charts which were among their most jealously guarded professional secrets.

It was thanks to Maury's initiative that the advantages of pooling navigational knowledge became so obvious that the way to the production of the present-day sailing directions and accurate charts was abruptly opened.

But the sea is a very big subject and has other physical aspects which have attracted scientific interest. In the seventeenth century Varenius published a *Geography of the lands and seas of the earth*, epitomizing the whole contemporary corpus of astronomical and meteorological knowledge and giving the first scientific description of the periodical phenomena which took place in the sea and which, incidentally, had already attracted the boundless curiosity of Leonardo da Vinci. Next, the fast-growing science of mathematics turned its attention to everything that could be brought within its sphere of reference, with Newton and Laplace proffering the first scientific explanation of the tides, and Bernouilli paving the way for the analysis of the motions of fluids by the future science of hydrodynamics. Concurrently great interest developed in everything relating to the sea. Zoology embarked on the description of marine animals, concurrently with the appearance of the first marine zoological collections, while geographers mapped out the ocean bed.

When the nineteenth century opened, scientists, economists, and politicians alike—the thinkers and the doers—had grasped the importance of the part played by the sea and everything connected with it in all human activities. Now men were no longer concerned to find new routes or new continents, to seek out new gold-mines or alternative sources of consumer goods, but only to extend their hold on a watery universe which they could not yet control and which only detailed knowledge, still completely lacking, would enable them to use for their own ends. Consciousness of ignorance in the matter

gradually increased, with the result that the great maritime nations began to dispatch scientific expeditions to every corner of the seas, following the example of the British *Challenger*, the world's first oceanographic ship to embark on a four-year course of ocean research. Thus oceanography was born, and the sea came into its own as a field of scientific study.

What, then, was the real nature of this world to which humanity was to devote so much energy?

### *The oceans and the marine world*

The terrestrial globe has a total surface area of 510 million square kilometres. Of this, the sea accounts for 361 million square kilometres or 70.8 per cent, leaving the land areas the modest share of 29.2 per cent. Therefore the planet we call Earth should really be called Ocean, the more so as the expanse of water whose influence extends to every clime and latitude, though divided arbitrarily into seas and oceans for geographical purposes, is in fact a single entity, the ocean, extending from north to south and from west to east, projecting northwards the three great arms of the Atlantic, Pacific and Indian oceans, fretted with the convolutions of the fringing or enclosed seas on their flanks, and to the south the Antarctic Ocean which girdles the South Pole.

The total volume of water in the sea occupying 70.8 per cent of the planet's surface is 1,370 million cubic kilometres, representing an over-all average depth of 3,800 metres, as against an average land altitude of 840 metres above sea level. In other words there would be an even depth of 2,440 metres of water covering our whole planet if the solids of the crust formed an even layer, instead of being crumpled and corrugated in the humps and hollows of syncline and anticline.

Moreover, contrary to what was believed for centuries, the ocean bed is not flat: indeed, the depth over 76 per cent of the area varies between 3,000 and 6,000 metres, and all the essential features are identical with those of land topography, the only difference being that, since there is no erosion, the elevations, at least in the case of the undersea mountain chains, still retain the shapes they assumed when they were first formed, though the hollows have mostly been filled in by sediment.

The sea itself is a solution and, now that analytical methods have become sufficiently precise to detect extremely small quantities, it has been found to contain, in solution, practically all the known natural elements of Mendeleieff's classification. Even where the concentrations are extremely low, the enormous volume of water involved still makes the ocean our planet's greatest depository of minerals of every description.

Then again, all forms of life started in the sea (that was well before the Precambrian age—nearly 2,000 million years ago) and still show a strong over-all predilection for the same environment. Indeed, the animal population

of the sea comprises some 300,000 species whose habitats range from the coastal shallows to the deepest cavities of the Pacific, and from sunlit waters to depths to which daylight never penetrates, illuminated solely by occasional flashes from the light organs of abyssal creatures. Here are found the microscopic organisms whose thousands of millions form the plankton which provides the whales with their chief noursihment; these are the largest creatures in the sea, often weighing as much as ten tons. There are also soft-bodied species like the medusae, or jelly-fish, so formed that they seem to blend into the water round them, to a point where it is sometimes difficult to distinguish between the creature and its environment; others, again, are veritable floating fortresses. Some species are vegetarian, others carnivorous; some sluggish, others active; some static, others mobile.

Furthermore the existence of the sea means 250,000 kilometres of coastline, with its havens and dangers; its inland-thrusting estuaries whose river communications with the interior make them the best ports and harbours; its rocky promontories acting as off-shore sentinels; its beaches and cliffs: in a word, a whole world of earth and stone endlessly remoulded by the waves—to man's profit when silting provides new room for human enterprise, or to his loss when erosion attacks his blockwork, harbour installations or sea defences. Nor is the sea significant only for the direct effects of its rhythmic physical motions, or for its amazing range of animal life: it makes itself felt in human affairs even far inland. Presenting a continuous fluid mass from the Poles to the Equator, its thermal inertia has something analogous to a 'flywheel effect' on extremes of temperature in tropical and polar regions alike, constantly modifying climates by partially transferring to colder regions the heat absorbed in low latitudes.

Moreover, while the great continental rivers discharge into the sea 13 million cubic kilometres of water every hour, the sea as steadily returns it to the atmosphere in an endless cycle in which the vapour drawn up from the sea by the sun forms clouds which travel as the winds direct, discharging on the most distant lands the rain or snow which mean life to them.

The sea, then, is the world's bank of minerals, organic substances, and thermal and dynamic energy derived from the sun; it regulates our climate, provides the earth with all its fresh water, and is the generator of all life, terrestrial and aquatic alike. What instruments, then, do we possess for prospecting its wealth?

### *Oceanography and its history*

What we have is oceanography generally, that is, the whole range of specialized 'marine' sciences—dynamics, dealing with horizontal and vertical circulation and, permanent or temporary, periodic or aperiodic water movements; physics, which is concerned with the sea's optical, acoustic, electric and similar

properties; chemistry, dealing with the nature and properties of sea-water and variations in those properties having associations with dynamic or biological phenomena; biology, studying the nature of the living creatures in the sea and the bionomy—or biological cycle—of the several species; and physical geography, geology and geophysics which are concerned with the morphology of coasts and the ocean bed, and the nature of the sediments and substrata appertaining thereto.

Oceanography really came into being during the voyage of the *Challenger* —the culmination of all the voyages for gain or knowledge, which from Columbus and Magellan downwards had gradually lifted the veil of ignorance and superstition hiding the sea. The *Challenger* was a four-masted corvette with auxiliary engines, and her cruise lasted four years. Under the guidance of Britain's most eminent scientists, research was carried out in every branch of marine science, and an amazing range and quantity of samples and specimens of every kind, as well as observations and measurements, was brought back to Edinburgh. The study, analysis and description of these data yielded the material for 40 volumes which, for many years after their publication, ranked as the standard work on oceanography, opening up all the main departments of oceanographical knowledge, more particularly with regard to the morphology and geology of the ocean bed and the physics and chemistry of the sea. These chapters were subsequently expanded, and will, it is hoped, be completed as the result of present and future research. Once the example had been given, it merely remained to follow it, and up to the second world war, similar cruises were frequently undertaken by German, French, American, Russian and Scandinavian scientific expeditions. The deep water areas were sought out and deeps (Puerto Rico, Mindanao, Japan, Mariana, Tonga-Kermadec, etc.) discovered, descending to 8,000 or 10,000 metres. Live species were collected at ever greater depths; the main features of the sea-floor relief began to be perceived, and observed data on the nature of the marine sediments gradually accumulated. As the methods for measuring physical and chemical properties, at sea and in the laboratory alike, improved, so did knowledge of the physics and chemistry of the sea become more accurate. Certain physical properties, such as density and specific heat, were quickly determined, whereas others, such as viscosity and transparency governed by the dynamics of water in motion, presented a more stubborn problem. Towards 1880 an accurate method of determining the composition of sea-water was discovered, and 20 years later its relative invariability was established. This is one of the most important facts in physical oceanography, since most of the salinity analyses so far published are based on the constant relation of salinity to the chlorine content. Next, studies were carried out on the influence of mineral salts, found in low concentrations in the upper levels of the sea, in the first phases of the nutritional cycle, and on the part they play—precisely analogous to that of soil fertilizers—in the photosynthesis of marine algae. The biologists, initially, concen-

trated almost entirely on descriptions of the vast numbers of species peopling the sea, but progressively, as more taxonomic categories came to be clearly established and their structure thoroughly determined, they shifted their attention to the complex interrelations of the different organisms with one another and with their environment. At last the dynamics of the sea began to be intelligible; not only did direct study of the major ocean currents make it possible to plot their course and evaluate their importance but the application to the study of the sea of fluid mechanics and of the theories worked out for atmospheric circulation provided a solid mathematical basis for our knowledge of the movements of water masses; while the description of surface and internal waves and of tides was facilitated by the development of hydrodynamics.

Such developments in research and the corresponding increase in the sum of knowledge were only possible as a result of the great improvements achieved in ocean observation and sampling techniques. Apart from the innovation of steam propulsion, the most spectacular progress has unquestionably been in deep-sounding methods which have progressed from the hand-operated deep-sea lead, and mechanical sounders with line and weight, to the modern continuous echo-sounder which does in a few seconds what would have taken, with the old mechanical sounder, several hours. To begin with, samples of ooze were taken with grabs or bottom samplers of only moderate efficiency. With the advent of the core sampler, however, there was steady improvement until sediment cores several metres in length could be secured. Water temperatures at different depths were measured with a degree of accuracy approaching a hundredth of a Centigrade degree, using the so-called 'reversing' thermometer specially designed for the purpose. Similarly, the introduction of reversing bottles, designed to be attached in succession to the operating line at the required depths, and tripped seriatim to enclose the samples, enabled 1- or 2-litre samples to be taken at any desired level, a built-in thermometer in each bottle giving the exact temperatures at the level sampled. Current meters of many types, both direct-reading and recording, were devised for fixed-point current measurement at different depths, while on the biological side dredges were designed for collecting organisms living at the bottom of the sea, as well as various types of sieve net for studying the distribution of microscopic animal life at all depths. Special sieve nets were also invented for studying the microscopic algae of the phytoplankton.

The second world war caused gigantic strides to be taken in oceanography. For tactical purposes, it became essential to know more about the physical properties of the sea and, in particular, its acoustics, sonic and ultrasonic detection methods having become of prime importance with the appearance of instruments such as Asdic, or directional beam ultrasonic range-finders. As the speed of sound transmission in water varies with the latter's density —i.e., with its temperature and salinity, the former being much the most important at the shallow depths at which submarines operate—the rapid measu-

rement of the continuous variations of temperature at different depths became a necessity. The result was the invention of the bathythermograph, which plots the variations down to 300 metres on a smoked glass plate. Increasing numbers of such measurements were thus secured from every region of the ocean, and the echo-sounders with which many naval vessels were equipped similarly yielded an endless harvest of soundings. Again, in view of the importance of coastal configuration, tides and tidal currents and the nature of the sea bottom in the planning of assault landings in war-time, investigation of conditions in coastal waters became widespread; new optical and photographic techniques were developed for the study of enemy coasts; and recourse was had to fluid mechanics to determine the effect of coastal configuration on swell-heave propagation and the influence of the atmosphere on the state of the sea.

After the war, as sonar continued to improve with steadily narrower and more accurate directional beams, so did the precision of the echo-recording equipment increase; the error for depths of over 5,000 metres is now less than one metre. Core samplers were completely transformed, so that it is now possible to extract cores 20 metres in length and thus be able to study sediments deposited about 150 million years ago, while seismic refraction methods afforded precise measurements of the thickness of sediments. Magnetic and gravimetric studies carried out at sea established a connexion between certain characteristics of the submarine topography and variations in the magnetic field, and made it possible to detect petroleum deposits; improved equipment for taking specimens allows of accurate work at any selected intermediate depth; buoys transmitting radio signals opened the way to the direct and widespread study of both surface and deep ocean currents; and radioactive tracers offered new methods for studying sediment dispersal and for evaluating the amount of living matter produced in the upper levels of the sea. The enlistment of electronics for research at sea made it possible not only to fix the positions of research vessels more accurately by radio navigation, but also to determine many variables on the spot, besides providing devices for the continuous measurement of variations in temperature and salinity according to depth; another apparatus devised was a direct-reading current meter for use by ships under way. In a word, oceanography has become the business of highly specialized scientists, drawn from disciplines as different as geophysics and chemistry, electronics and pure mathematics; and research at sea has become a team job, with the effectiveness of each one's work dependent on the backing of the team as a whole. For the fact is that any advance in one direction incidentally increases the general sum of knowledge, since in the sea the tiniest particle settling on the ooze in the profoundest deep is the end-product of a vast complex of phenomena of which some at least have no direct connexion either with submarine geology or with sedimentation.

## OCEANOGRAPHY AND CIVILIZATION IN THE TWENTIETH CENTURY

Although the sea has been a source of inspiration to a great many poets, story-tellers and musicians, there can be no doubt that it is in the economic sphere that its influence has been greatest. It is therefore not surprising that when oceanographical research has had practical implications the result has usually been an improvement of the world economic situation, apart from any influence that wars may have had on the development of the marine sciences. Among the human activities more closely connected with the sea which have benefited most from research, there are three whose importance extends far beyond the circle of the maritime nations proper and which take immediate rank as common world interests. They are the fishing industry, the extraction of raw materials from the sea and navigation. A rapid analysis will show the part so far played by various departments of oceanography in the conduct of these three basic activities of mankind.

### *Oceanography and the fishing industry*

The annual fisheries statistics of FAO show that 24.2 million tons of fish and shellfish were taken from the sea in 1954. Fishing is thus the largest as well as the oldest of the extraction industries exploiting ocean resources. It has however certain characteristics which render it somewhat unbalanced.

Thus, the Southern Hemisphere contains 57 per cent of the world's sea area, but 72 per cent of the world's fisheries are located in the Northern Hemisphere where the population is denser, and the level of industrialization more conducive to a rapid development of large-scale fishing, and where shallow areas, fishable by the highest-yielding methods, such as the bottom-trawl, are more extensive.

Again, while the number of different species caught is remarkably large, the bulk of the catch—between 70 and 80 per cent—of the countries with the biggest output, e.g., Japan, the United States, Great Britain, Scandinavia, is represented by a very few species, notably cod, hake, haddock, herring, sardines, anchovy, tunny, bonito and mackerel. The result is that for these heavily fished species the rate of extraction is very near the limit beyond which intensive methods would lead to over-fishing and the disappearance of the species most sought after.

Finally, while large quantities of other kinds of fish are caught for processing into cattle food and industrial oils (e.g., the Scandinavian herring and the menhaden in the United States) and not for direct human consumption, others again are available in abundance but are not fished at all for lack of outlet, as commercial dealings in fish in the great world markets are confined to a few species only. Finally, 'deep-sea' fishing is everywhere restricted to

off-shore waters, shallow seas and the continental shelf, the only exception being the deep-sea tunny grounds in the Pacific.

All this notwithstanding, the industry is growing at a prodigious rate, and between 1948 and 1955 the tonnage of landings throughout the world increased by 40 per cent, from 19.4 to 27.7 million tons. Naturally one reason for the rise is the increase in the number of fishing vessels; but another important factor is the improvement in fishing methods due to our growing knowledge of the biology of the species exploited and their environments.

For instance, the marine alimentary chain ranging from the minute floating algae, which are, as it were, the 'grass' of the sea, to the predatory species hunting prey of all sizes and themselves hunted by man, has far more links than its terrestrial equivalent, and each transfer of 'food value' from a given biological level to the better organized level next above it involves a heavy loss in the amount recoverable. Again, the currently accepted assumption is that the quantities of organic matter produced by photosynthesis in the sea and on the land respectively are equivalent. But at sea the process is spread over an area twice as great as on land, and continues to depths of from 20 to 100 metres according to latitude, instead of being confined to a surface layer only; this means that living matter of marine origin is more dispersed and hence harder to collect. Again, photosynthesis rapidly exhausts the dissolved nutrient salts in the upper levels of the sea (the role of these salts is identical with that of fertilizers on land) and, after the completion of a few cycles, the production of organic matter by the action of solar energy on the chlorophyll of the algae is only possible if the nutrient salts used up are replaced in adequate quantities. There are three types of mechanism to effect this. First, richer subsurface water may be mixed with the surface layer by upward vertical displacement off shore, or at the interface of two markedly different water masses when the wind is sufficiently strong to displace the surface layer laterally, and subsurface water rises to replace it; the result is what oceanographers call 'upwelling', or divergence. The second method is through loss of heat when the surface water becomes heavier than the richer layers below it, sinks through these layers and leaves them on top; and the third is intense vertical turbulence where the permanent ocean currents meet.

These phenomena—the 'ploughing' of the sea by itself, as it were, enable the surface layers reached by sunlight to carry a heavy load of seaweed and thus promote concentration of the miscroscopic animal organisms forming the zooplankton, the basic food of fish. Thus oceanography indicates that areas of strong vertical movement offer the best prospects for the development of commercial fishing, and the facts bear this out: upwellings due to wind conditions are responsible for the growth of extremely important fishing industries, e.g., for sardines on the Californian coast, in South Africa and on the coast of Morocco, and for tunny along the Pacific coast of the Americas, more particularly along the Chilean and Peruvian coasts, where the upwelling

is one of the most intense in the world. An important secondary consequence in this latter area is the guano industry, which is due to the millions of tons of fish consumed every year by immense numbers of sea birds.

The winter temperature-loss mechanism favours the cod, herring and haddock fisheries of Newfoundland, Iceland, Greenland, Labrador and the Barents Sea, as well as the whaling industry in the Antarctic, where the sea is fertilized by water from the North Pole which flows into the North Atlantic and traverses it from north to south along the bottom, picking up more and more nutrient salts as it moves towards the South Pole. Examples of good fishing grounds created by vertical turbulence are the meeting places of the warm Gulf Stream and cold Labrador Current in the Atlantic (Maine sardine fisheries), and of the hot Kuroshivo and cold Oyashivo currents off the Japanese coasts (sardine and herring fisheries of Japan).

Thus oceanography today enables us to give a scientific explanation of why the major fishing grounds are there. However, it does more than simply interpret existing situations, and the most striking example of this is its discovery of new tunny fisheries in the equatorial Pacific, where the north and south equatorial currents and counter-currents meet. Research revealed that this region was specially rich in plankton, and was therefore liable to carry a heavy population of predatory species; subsequent tests did in fact show that pelagic tunny were to be found there in large numbers.

Another thing that oceanography can do for the fishing industry is to find an explanation for the fluctuations that occur every year in the landings of individual species and from this, to forecast such fluctuations so that fishing techniques can be modified accordingly and fishing operations transferred, if need be, to other areas. The size of catches depends on the quantities of fish available, and the latter on the balance achieved between the net rate of natural increase of the fish population by reproduction and the rate of loss by normal mortality or fishing. When, for a given geographical density, the last two factors outweigh the first, numbers fall and catches shrink. The net rate of growth and reproductive increase of a given species is determined by its bionomy, and therefore varies with the environment, depending on the organism's degree of adaptation to physical conditions, such as temperature and salinity, and on the quantity of nutriments available, the latter—as we have seen—depending on the movements of water masses. When, for specific meteorological reasons, there is a sudden change in the physical climate of the environment, or a drop in the rate of replacement of nutrient salts in the upper levels of the sea, the increase-decrease balance of the fish population is completely upset, with catastrophic effects on catches and hence on the economy of a whole coastal region. A typical example of this is the almost complete disappearance of sardines from Californian coastal waters in 1950, which persisted for several years and practically wiped out a trade turnover reckoned in hundreds of thousands of tons in previous years. The cause was a slight

change in the pattern of the winds responsible for the upwelling off California, reducing it to such an extent that the sardines practically stopped breeding and their numbers fell so low that any commercial exploitation was impossible. This continued until the wind pattern returned to normal with a renewal of strong off-shore upwellings. Detailed knowledge of such mechanism in which a meteorological situation reacts on an oceanographic one which in turn may influence the biological aspect, makes it possible to foresee developments of this kind and to adopt the measures of adjustment essential to maintain the balance of the economy of the zone affected.

Another aspect of the connexion between fishing and environment is the fact that practically all the major fishing grounds are supplied by the trophic (feeding) or breeding migrations of the species concerned. With an intimate knowledge of the mating habits of fishes, of the biology of the organisms on which they feed and of how both are affected by environment, forecasts can be made, well in advance, of the times when the schools will be on the move, the depth at which they will be found and the zones of highest concentration. This fact, taken in conjunction with the improvement in fishing techniques and, more particularly, the use of echo-sounders which enable the position of the schools to be plotted with great accuracy, opens the way to a more scientific and, above all, more effective working of the innumerable sources of living wealth hidden in the sea.

*The sea as a source of raw materials and energy*

Salt water, it will be recalled, can be reckoned for all practical purposes to hold all known elements in solution. While the concentrations of individual items vary, the over-all content is about 35 grammes of salts per litre, and there are nearly 1,300 million cubic kilometres of water in the world's seas, thus putting our reserves of sodium chloride, or ordinary kitchen salt, at the respectable figure of 38,000 milliards of tons. These facts indicate one of the most fundamental aspects of the sea's role *vis-à-vis* mankind, for it is the world's reserve of many raw materials which are more abundant there than anywhere else. True, the price is sometimes a little high, for in many cases the concentrations are so low that the cost of extraction, in the present state of our technology, vastly exceeds the value of the product, as the chemist Haber discovered on the 1924-28 Atlantic cruise of the *Meteor*. His idea had been to help Germany pay its war debts by extracting gold from the sea, and he accordingly embarked on a painstaking investigation of the concentrations of the precious metals and the best way of separating them from the other elements. There are indeed vast quantities of gold (10,000 million tons) in the sea, and 50 times as much silver, but the concentrations are so low (gold: 0.0003 milligrams per litre; silver: 0.000006 milligrams per litre) that it was

soon obvious that processing costs (concentration and extraction) would be prohibitive; Haber therefore abandoned the idea.

However the sea is not always so close-fisted. World consumption of salt is around 25 million tons per year and all of it is of marine origin, whether evaporated direct—to a mean annual tune of 10 million tons—from the many coastal salt-pans of the hot countries, or extracted from rock-salt mines which are the remains of ancient, dried-up seas. Apart from the fact that every one of the world's inhabitants consumes 8 kilograms of this sodium chloride per annum, it is also a basic raw material for the chemical industry for the manufacture of carbonates and bicarbonates of soda, hydrochloric acid, hypochlorites and perchlorates.

Magnesium, a metal vital to the aircraft industry, is almost entirely derived from sea-water, which contains over a kilogram per cubic metre; and the same applies to potassium, used for making fertilizers and in the chemical industry, and bromine which is an ingredient in anti-detonants used in high-octane fuel, sedatives, dyestuffs and photographic material, and of which 99 per cent of the world's reserves are found in the sea.

The algae, found in thick masses along many coasts are also a source of wealth, and an inexhaustible one, since they grow again as fast as they are harvested. There are three main groups—green, brown and red—and nearly 500,000 tons per year are taken from the sea. In some places they are used as food, particularly in Hawaii and in Japan where the green type is eaten; and whereas they were formerly the main source of soda for the glass and soap industries, and of potassium and of iodine, they have now become an important source of basic raw materials. Thus, the brown algae yield a colloidal material similar to cellulose and known as algin, which is an excellent emulsifier and thickener, extensively used in the food, pharmaceutical and textile industries, while the red algae also yield thickeners and emulsifiers and in addition, carbohydrates for the food industry and agar-agar, or gelose, which is used in pharmaceutics as an excipient, and in bacteriology as a culture base.

Oceanography has further provided the means, in specially favourable parts of continental shelves, of plotting the sedimentary deposits liable to hold deposits of petroleum or natural gas, by applying geophysical prospection techniques to ocean research. The three in most general use are the gravimetric, which deals with the gravitational anomalies associated with differences in rock density; the geomagnetic, by means of which the distribution of sedimentary formations can be plotted by measuring anomalies in the earth's magnetic field; and the seismic, which enables a preliminary picture of the nature and thickness of the successive sedimentary strata to be obtained by analysing the rate of propagation of artificial shock waves. All these methods have been used on a large scale, particularly in the Gulf of Mexico, off the coast of California, in the Persian Gulf, in the Caspian and in the Black Sea, and have opened the way to the working of submarine petroleum deposits, which is

now current practice in some regions, e.g., the coastal waters of Texas, Louisiana and California.

Another new prospect opened up—by the discovery that there is marked thermal stratification in the upper layers of the sea, particularly in middle and low latitudes—is that of tapping the vast supplies of power known as the thermal energy of the sea. As it has already been demonstrated that a turbine can be run with low pressure steam at a few hundredths of an atmosphere, there is no reason why use should not be made of the difference between the temperature of the surface levels in tropical seas, which is always above 20°C., and of the underlying levels in which it falls to below 10°C. comparatively near the surface. After removal of the dissolved gas, the surface water will become steam in a partial vacuum, and this can then be used in a turbine running in a vacuum, condensation taking place on contact with cold water pumped from the necessary depth. Part of the energy produced by the turbine is used up by the gas removal system, the vacuum pumps and the warm and cold water circulating pump, but a surplus will be left for industrial power supply. The low cost of installing plant in coastal areas where the configuration and hydrological régime are such that sea-water can be raised from the deep layers without too much difficulty, make this an extremely attractive source of energy, the more so as it does not depend on any fuel doomed to ultimate exhaustion, since the indefinite continuance of thermal stratification in the sea is guaranteed by the action of the sun.

The sun's action also guarantees the permanence of other inexhaustible reserves of energy, the swell-heave, the waves and the tides. While numerous attempts have been made to use the swell-heave or the waves for small- or large-scale power supply, they have all been more or less unsuccessful on account, firstly, of the intermittent occurrence of the required conditions, and secondly of the enormous energy released during a storm by the waves which can easily shift objects of several tons weight. The position is otherwise as regards the harnessing of the tides. In certain special areas such as the Bay of Fundy, the Severn Estuary or the Bay of Mont St. Michel, there is a very marked difference between high and low water level, 10 metres being nothing out of the common. With this happening twice daily throughout the year, the inducement to try to put it to practical use was a powerful one, and this was finally yielded to when the decision was taken to build a tidal generating station with 18 units of 20,000 kilowatts each in the estuary of the Rance; France was also responsible for the first attempt at harnessing the thermal energy of the sea with a 7,000-kilowatt generating plant at Abidjan.

Obviously, the discovery of new ways of using the sea and its reserves has posed a multitude of scientific and technological problems and represents the outcome of a long series of investigations. Extracting chemicals from sea-water involves a thorough knowledge of what is an extremely complex medium. Installing a tidal generating station which interferes with the normal propa-

gation of the tide along the coast entails intricate research to ascertain its effects on the neighbouring coastal regime. Whenever industrial plant is in contact with sea-water, difficult corrosion problems arise. Only the vast strides made in recent years in the study of marine physiology, chemistry, geology, dynamics and many other branches of oceanography have made it possible for our methods of exploiting marine resources of all kinds to develop as they have.

### *The sea as the world's chief trade route*

World history and the history of the growth of international trade go hand in hand. From the earliest times the seas have been used not only for overseas trade but for short- and medium-range coastal traffic between places in the same country; and everywhere the sea antedated roads as the gateway through which sovereign States achieved economic and political progress. Just as improvements in maritime transport for long depended on advances in our knowledge of the sea, of coastal topography and of winds and currents, so today are such improvements in many respects bound up with the progress of oceanography which is still destined to play a decisive role in the exploitation of the world's great trade routes.

Keeping a ship at sea may run to a considerable sum per day. Accordingly, whenever a vessel—cargo or passenger—is to make an ocean passage, the course plotted makes allowance, firstly, for the nature, strength and direction of the major ocean currents which might be met with *en route*, representing a gain or loss of costly hours or even days, and secondly, for the prevailing meteorological conditions, their probable evolution, and their effect—calculable with a high degree of accuracy—on the state of the sea. Thus oceanography's study of the major currents such as the Gulf Stream, the Labrador Current and the equatorial currents, their causes, courses and fluctuations, has rendered priceless service to international trade.

Nor, with the world's coasts exposed to the swell and battered by the waves along most of their length, would international trade have reached its present volume had not a kindly providence provided peaceful havens here and there where ships can load and discharge in safety, and had not man built others wherever nature had been too niggardly, and his business needed wharfs, quays and docks. These harbours, natural and man-made, are under continuous assault from the swell, the waves and the currents. This may take the form of a direct attack on the protective works or, more insidiously, of an invasion of silt blocking the basins and channels. In the first case the whole port would sooner or later be overwhelmed by the waves and would be left miles inland, high and dry. Men have therefore had to create a whole science of coastal defence, building moles and breakwaters or modifying the forms of harbour works wherever it is necessary to deflect a current, create an artificial bed of

silt or check swell-heave. All this must be based on a profound knowledge of the coastal dynamics and the associated tidal and current régimes, as well as of the régime of swell-heave and waves, whose propagation is affected by every shallow or headland, being ultimately linked with the prevailing meteorological régime and the interaction of sea and atmosphere. Thus meteorology and dynamics, hydraulics and sedimentation, are essential factors in questions pertaining to coastal developments. Again, not only must the ports be kept in an efficient state to handle the traffic based on them: the coasts on which they lie must also be safe for navigation, i.e., all the dangers and hazards they present for vessels of varying tonnage must be fully ascertained, recorded and 'pin-pointed'. This is usually the task of national hydrographic services which are responsible for producing detailed charts of coastal waters giving all necessary information on currents, shallows, leading marks, etc. These charting operations, formerly carried out by laborious soundings with the hand-lead, can now be executed much more rapidly thanks to the introduction of ultrasonic echo-sounders: but while some coastal areas, where ocean traffic has always been heavy, are remarkably well-charted, there are others, mostly in the underdeveloped countries, where the task remains a gigantic one. In such cases only revolutionary methods can give rapid results, but they do exist, the war having helped their development. Where there is a sand bottom, photographs of the bottom seen through the water are scanned for variations in the brilliance of the sand, which varies according to its depth; while for general use on any coast the characteristics of the waves are first observed in deep water, the depth being then determined by noting the changes in their height and speed of translation, both of which depend on the intensity of friction against the bottom, which varies with the depth. Here again, the technician has found unintended but not unprofitable ways of applying the purely theoretical studies which oceanography has developed over the last few years.

## FUTURE PROSPECTS

The science of oceanography is less than a hundred years old, and for a long time was cultivated only by a few rich maritime nations in the interests of pure science. Technologically, here as elsewhere, the circumstances created by the two last world wars have been of enormous help, and oceanography can now claim credit for some notable technical advances and for having made a definite contribution towards improving the world's standard of living. The benefits it has conferred on humanity, however, do not stop there, and a still more brilliant future may be predicted for it on the assumption that modern society will evolve along lines which will make it necessary to resort increasingly to the sea for food, industrial raw materials and energy.

*Food reserves and their utilization*

We have seen that oceanography has several times played a part in the progress of the fishing industry, by throwing new light both on the biology of the most sought-after species and the extent to which these fish are affected by their physical environment. Fisheries research necessarily entails a study of the species most suitable for intensive exploitation, the over-all population pattern of each and the extent to which that pattern is affected by modifications in the environment, or by conditions in the industry itself; and its objects are to find practical answers to questions relating to the different types of fish, where they are to be found, and in what quantities, and their reactions to various stimuli.

In marine zoogeography, more particularly with regard to the distribution of fish, our knowledge of the heavily fished zones is fairly good, but we know practically nothing about the rest of the ocean—in other words the greater part of it; yet areas hitherto considered completely sterile may in fact contain commercial quantities of usable species. Recent cases in point are the Bering Sea with its rich new crab grounds, the Gulf of Mexico with its shrimps and the equatorial Pacific where deep-water tunny is found. It is therefore the responsibility of oceanography to make a full inventory of the sea's resources, to record particulars of the water-mass characteristics liable to influence the distribution of the various fish populations, and to furnish the fisheries biologist with all relevant data on variations in their physical conditions so as to enable him to forecast the reactions of the fish to their environment.

Physical, chemical and biological specificities should also facilitate the observation of variations in the abundance of fish. Abundance is obviously dependent on the environmental conditions that determine a region's productivity, namely, its climate and the condition, dynamic or otherwise, of the water; and general studies should therefore furnish the means for calculating in advance the likelihood of a particular region being able to support a given fish population. However, quantity variations are also determined by the balance achieved between rates of reproduction and increase and mortality; the former depend both on genetic and on external factors. Oceanography's role will be to study 'feed' availabilities, population increase, variations in age-group patterns and the rate of production of organic matter, all of which are important factors in the prognosis.

Although the trend in the fishing industry will be towards the maximum exploitation of ocean resources, those represented by living creatures, at any rate, are not inexhaustible, but belong to the category of what might be called 'self-stabilizing' resources, inasmuch as replenishment rates are conditioned not only by physical environment, but also by the size of the population itself which of course will vary according to the intensity of exploitation in any

given region. Oceanography will help to determine, for each species, the optimum rates of extraction representing the happy mean between under- and overfishing, as has already been done for whaling; by systematic study of the distribution of marine life, it will locate new fishing grounds; and it will increase catches by developing methods for predicting when and where large concentrations can be expected.

Finally, by encouraging the modernization of fishing methods, oceanography will also help to open up new sources of supply. It must be remembered that, apart from the application of electronics to navigation and the detection of fish concentrations, there has been little change in equipment and techniques over the centuries; and a major consequence of their relative inefficiency is that operations are normally confined to high-density fish populations. It is estimated that a commercially viable density in terms of current costs and prices, is represented by a proportion of 10-50 grammes weight of fish per square metre. Densities of this order are comparatively rare and confined to strictly delimited coastal areas, which accounts for the unbalanced distribution of the major fishing grounds already mentioned. But it is highly probable that species found in concentrations below the critical figures cited, and not at present a commercial proposition, constitute a biomass, i.e., a self-contained live population, many times greater than that represented by the exceptionally gregarious species, which will become 'fishable' when, say, techniques have been developed for 'rounding-up' the fish so that traditional methods can be used.

The creation of magnetic, electric or acoustic fields in the sea appears to be the solution of the future, but at present little is known of the reactions of the fish to such stimuli.

In any case the ultimate aim is to abandon aleatory catches for systematic 'harvesting'.

The harvesting idea can further be applied to the plankton. If we bear in mind the fact that in the marine nutritional cycle from nine-tenths to nineteen-twentieths of the food consumed at each biological level is absorbed by the consumer's basic metabolism and only a remnant of a tenth or twentieth part of it is 'stored', it follows that fish account for no more than one thousandth, or even one ten-thousandth part of the food value represented by the algae of the phytoplankton, which is ten to twenty times more plentiful than the zooplankton. In quantitative terms, therefore, zooplankton can be regarded as a far from negligible source of animal protein, and its food value, already proved by the fact that some whales live on it exclusively, has been confirmed by the Kon-Tiki Expedition and by Dr. Bombard's Atlantic voyage. The idea of harvesting the plankton and thus eliminating the vast losses that occur at every stage in the nutritional chain, has therefore much to recommend it. It does not appear to be immediately practicable, owing to the extremely low concentration of the 'crop'—1 kilogram of protein by weight to

about a thousand tons of water—but the idea can be revived for serious consideration when a technique has been developed for low-cost filtration of enormous volumes of water.

Another possibility for the future is direct human intervention at the start of the nutritional cycle. We know that, to enable them to grow the microscopic algae need not only light and carbonic acid gas—always available in the upper layers in adequate quantities—but also nutrient salts such as phosphate, nitrate and silicate which occur only in very small quantities, and would quickly be used up but for the operation of replacement mechanisms. The only 'fertile' parts of the sea are those where these mechanisms operate exceptionally powerfully, owing either to a special wind régime or to intense winter surface-chilling, liable to cause upwelling. The creation of artificial upwellings elsewhere would cause a corresponding increase in the number of fertile zones of the sea. For instance, means could be devised for warming up the lower layers locally, when they would become lighter and tend to rise towards the surface; sunken nuclear reactors have already been suggested as a heat source. 'Aquiculture' can also be carried out in certain cases by enriching the higher water levels with the necessary nutrient salts. This operation however can only be a commercial proposition when the volume of water is slight, i.e., in lakes and relatively shallow land-locked bays, or in coastal regions where the dynamic régime is such that the water remains undisturbed for relatively long periods.

*Energy and mineral reserves*

The discovery of submarine petroleum deposits has given considerable impetus to the geophysical prospection of the continental shelf—i.e., of the relatively flat part of the submerged continental mass running down from the waterline to a depth of about 200 metres, when the angle of slope mostly changes and there is a steep plunge into deep water. The shelf is a submerged extension of the adjacent land mass and, having undergone the same upheavals and submersions, is the same in structure and hence in mineral resources. It is estimated that the total continental shelf area of the world contains some 120 million cubic kilometres of petroliferous sediments, with a reserve of crude oil of about 400 thousand million barrels, or nearly 40,000 million tons. This is equivalent to one-third of the world's total reserves, to 45 times the 1956 consumption figure and to nearly 5 per cent of the total reserves of fossil energy. It will thus be apparent that the possibilities of the sea as an oilfield are far from negligible, and that extraction will be extended, as fast as sea-drilling techniques are improved, to increasingly greater depths, the sole obstacles at present being the effects of corrosion, swell-heave and waves on equipment not designed for working under such severe conditions.

Another prospect is that coastal development works will afford fresh possibilities for using the tides for power production. In view of the lower operating

costs of tidal generating stations, it is probable that under certain conditions, and when the coastal configuration makes their installation relatively easy, it would be more economical to use them rather than have recourse to atomic power. The fact that the projected Severn Estuary scheme is expected to yield 2.3 thousand million kilowatt-hours, the Cobscook Bay scheme (Fundy Bay), 340 million kilowatt-hours and the Mont St. Michel scheme 12.5 thousand million kilowatt-hours, shows that there are massive reserves of energy still available in the sea, apart from its other reserves in the form of thermal energy, which will be on the market as soon as a few technological obstacles have been overcome. Both types of energy are the more important in that they belong to the category of permanent marine resources which can be drawn on indefinitely and can never be exhausted.

Spectacular developments, over the last few years, in submarine geology and the techniques of 'abyssal' photography have served to reveal that great stretches of the sea bottom are covered with metalliferous concretions, called nodules, mainly iron and manganese oxides, but with an admixture of appreciable quantities of rarer metals such as nickel, cobalt and copper. Considering the immense area involved, this represents a reserve of minerals of incalculable richness, and steps will certainly be taken to exploit it when land supplies are exhausted. The areas are ready to hand, and only technical difficulties stand in the way of their being worked forthwith.

The sea also has other marine mineral resources which will become extremely important, once economical methods of extraction from sea-water have been perfected. Already the residual brine of salt marshes yields sodium sulphate, potassium chloride, magnesium chloride and oxychloride of magnesium. Borax, bromine and lithium, and salts of potassium and sodium are extracted from extinct seas such as Lake Searles in California, and from the Dead Sea where the degree of salinity is 10 times greater than in the ocean; and what time and nature have done again and again and throughout Earth's geological history man can try to reproduce with all and any of the energy sources at his command. For instance, engineers may be led to use nuclear power to get fresh water from salt for the reclamation of areas which are now arid, reducing the costs of the operation by recovering the kinds of industrial raw materials referred to above from the residual brine; they might even get uranium which is found in solution in sea-water in such high concentration that its fission would yield 100 times the amount of energy required to evaporate the water. Of course, when we reckon out the details of such an operation and compare them with the action of the sun on the sea and the energy expenditure represented by evaporation from the ocean surface—10,000 times man's total consumption of power from all sources, coal, petroleum and hydro-electric power put together—we can see that our means of modifying the situation are limited and our radius of action extremely restricted. However, an idea is gradually gaining ground that the balance of energies which regulate the inter-

actions of sea and atmosphere and produce the climates that we know is metastable to the same degree that certain atmospheric processes are found to be so. A slight pressure on some local phenomenon could lead to large-scale modifications. When the mechanisms controlling weather and climates are fully known, it will probably be possible to identify the climatic sensitive points on which man can operate to modify atmospheric conditions as required. For instance a possible subject for serious and exhaustive investigation would be the idea of using nuclear power to melt part of the Arctic ice-cap which blocks Siberian sea communications, although it is suspected that doing this might provoke an excessive extension of glaciers in Europe and North America; up to now the idea has been rejected in view of the possibility that the dry winds from the north might pick up moisture in their passage over an Arctic Ocean free of ice and empty their clouds on the already snow-capped mountains of the Northern Hemisphere, thus bringing about a gradual fall of temperature. Conversely, a rise in mean temperatures might possibly result from the present-day excessive consumption of coal, petroleum and other combustibles, with the consequent discharge of vast tonnages of carbon dioxide into the atmosphere. Part of this is absorbed by the sea, but the rest goes to raise the atmosphere's $CO_2$ content and may in the long run increase air temperatures by 1° to 2°C. by holding back long-wave radiations near the earth's surface. The result could be a chain reaction culminating in the melting of the polar ice and consequent submersion of great areas of the present land masses. The fate of mankind depends on the sea's power to absorb carbon dioxide and on the cyclic mechanism which raises all the subjacent water layers successively to the surface. Here again man could intervene in an attempt to restore the balance upset by his own interference.

Finally, as man's future as a power user depends on the harnessing of thermonuclear energy, it should be borne in mind that the sea is the world's greatest hydrogen reserve.

*Maritime transport and its development*

For the moment there are many factors limiting the progress of maritime transport. Among the most important would appear to be the size of ships, the obstacles to navigation presented by ice, the limited capacity of harbour installations and inadequate freight-handling techniques (baling, etc., loading and discharging).

As regards the size of vessels, the adoption of atomic energy for propulsion, a fuller knowledge of the action of the sea on hulls and improvements in the protective paints used to prevent fouling (which adds considerably to maintenance costs) should do much to facilitate and speed up overseas trade. Another prospect for the future is the use of atom-powered icebreakers: if this became

general, it would be possible, with no expenditure on fuel involved, to keep certain routes now closed to winter traffic permanently open. Finally, the recent exploit of the *Nautilus* suggests the possibility that one day submarine navigation may become of considerable commercial importance; its advantages are, firstly, that ships' insulation from surface disturbances makes their movements independent of meteorological conditions, and secondly that the north polar route can be used, which in some instances reduces the length of the passage by half.

A ship's earnings also depend on freight-handling techniques, as indicated earlier, and are affected by the capacity of harbour installations, which in turn, are conditioned by the nature of the sites where the port has grown up. Moreover all ports, whether natural or artificial, are under constant pressure from the action of the sea with its tendency to change and destroy what man has built. Resisting the destructive action of the sea is an inescapable necessity for engineers, and construction and protective techniques must evolve to keep pace with the growth of our knowledge of the processes in operation along the coasts.

*The sea as a dumping-ground for industrial waste products*

It has always been thought quite natural to discharge the refuse of coastal towns into the sea. A fact which has, however, little by little become apparent is that the effects of the inconsidered use of the sea as a midden on its fauna and flora might be catastrophic when local conditions do not permit of the rapid mixing of liquid sewage with sea-water and the dispersion of water thus polluted.

The construction of any sewage outfall into the sea should therefore be preceded by a comprehensive study of the prevailing tides and currents, of the density of distribution according to depth, of mixing rates, and of the rate of elimination of dangerous bacteria; and the choice of site should be made in the light of the information thus obtained.

In the same general connexion, incidentally, a problem of critical urgency is posed by the highly dangerous radio-active waste from nuclear industries, which is being produced in ever-increasing quantities. It can neither be destroyed, neutralized, nor used for anything, and as there are few land areas where it can be dumped without danger to man, a solution mooted is to embed it completely in cement blocks and dump these into the ocean deeps, or wherever it is judged that the water is static. Nevertheless, this procedure is only safe provided the water really is static, or its movement so slow that the abyssal water will take several thousand years before it reaches the surface or comes in contact with animal and plant life, and will by then be completely free of any form of radiation dangerous to man.

## CONCLUSION

Just as Jourdain spoke prose so mariners for many centuries were oceanographers without knowing it. While oceanography, pre-eminently a 'high-cost' science with an influence on innumerable human activities, has never received the publicity with which other examples of man's spirit of discovery have been hailed, the fact remains that all those with any degree of responsibility for the future course of the world's economy are becoming daily more aware of the part which the sea must play in the relatively near future.

In view of the rapid and almost universal rise in standards of living and the consequent readily calculable increase in man's requirements in industrial raw materials and energy, it is clear that the natural resources of the earth will not long be able to meet the enhanced demand for animal and vegetable proteins, coal, petroleum and metals.

It follows that the sea with its inexhaustible reserves will be the first 'extra-terrestrial' source of these products on which we shall have to draw, long before the moon or some planet or other is in a position to supply them in appreciable quantities. Fisheries will expand and be carried on more scientifically; large quantities of protein will probably be extracted from plankton, and 'aquiculture' will be developed in suitable areas, with methodically worked 'fields' of algae yielding food and industrial raw materials. The sea will be harnessed to supply low-cost energy to countries not possessing their own natural hydroelectric or fossil fuel power sources, and part of the power available will be used for working the mineral reserves in solution in seawater, or embedded in the abyssal ooze.

While there is nothing far-fetched about this picture, it will only become a reality when certain prerequisite conditions have been met.

First and foremost, improvements are essential in the quality and quantity of the tools available to oceanographers—laboratories, ships, and general and research equipment. In relation to what they have to do, they seem, indeed, today to be ludicrously inadequate. Some countries have understood this and have started national oceanographical institutes with considerable funds at their disposal contributed by various departmental budgets (e.g., defence, industry), and equipped with large vessels for work at sea. Examples are Japan, the Union of Soviet Socialist Republics and the United States, all of which possess equipment unrivalled by that of any other country, and are financing the work on a scale which would have seemed extravagant only a few years ago; for instance, the United States has allocated $58 million for oceanography in 1960.

The last condition is the most important: with the universal ocean lapping every shore and posing problems of every description involving a multitude of sciences, no single nation can claim to grasp the sea's true significance or

understand its inner life. Research therefore, in its eternal pursuit of greater efficiency, must inevitably be organized on an international basis. The joint operations conducted in the North and equatorial Pacific by Canadian, American, Japanese and French vessels, and the era of international co-operation inaugurated in connexion with the International Geophysical Year, point the way which will be followed by oceanography in the years to come, thus presenting the maritime nations with fresh opportunities for better mutual understanding and more effective mutual help.

# MARINE OPTICS

*by*

Y. LE GRAND

*Y. Le Grand, Docteur ès Sciences, has been a professor at the Muséum National d'Histoire Naturelle and the Institut Océanographique, Paris, since 1949. His two specialities are the optics of sight and marine optics. He is the French representative on the Special Committee on Oceanographic Research (SCOR) of the International Council of Scientific Unions.*

The sun's rays are the earth's main source of energy. By photosynthesis, plants fix part of this energy in the form of carbohydrate compounds. The herbivorous animals which eat the plants and the carnivorous animals which devour herbivorous prey appropriate only a fraction of the energy thus obtained. Ultimately, all life depends more or less directly on the sun.

Moreover, about three-quarters of the earth's surface is covered by oceans; these provide an additional living environment, of which the third dimension is important, since the average depth of the sea is two and a half miles, whereas the average thickness of the land and air element is far less. The scope of marine biology is therefore much greater than that of land biology.

Hence, the problem of the penetration of the sea by the sun's rays is fundamental for the general economy of life on the earth. Moreover, the study of the deep ocean by visual means, both direct (bathyscaphe) and indirect (photography, television) has developed considerably in recent years. It would, for these reasons, appear useful to present current data on marine optics, that is, on the penetration, absorption, diffusion, polarization, etc., of electromagnetic radiations in the oceans.

## TRANSPARENCY

A few fathoms beneath the surface, water is practically impervious to radiation, the reasons for this differing according to the wavelength. Because of its electrical conductivity salt water absorbs long radio waves or even the shorter radar waves immediately. Infra-red rays are also quickly absorbed, not as a result of ion conduction, but by the water molecules themselves; short wavelengths—ultra-violet, X and gamma rays—are checked by electrons or, atomic nuclei. Lastly, apart from certain highly penetrating cosmic rays, water is transparent only for radiations of the 'visible' spectrum and the near ultra-violet.

This similarity between the degree of transparency of the sea and the very small group of radiations to which the human, and animal, retina is sensitive

is certainly not a pure coincidence: comparative biology teaches us that the sight organs of all animals perceive practically the same light, with very slight variations (for instance, insects see farther than vertebrates into the ultra-violet, because their composite eyes are in no danger of being hampered by chromatic aberration due to ultra-violet radiation, which, for image-perceiving eyes, impairs sharpness). The phenomenon is not very surprising, if it is assumed that life originated in the oceans.

The origin of the Purkinjee effect can probably be explained in a similar way. This term is used in physiological optics to describe the shift of retinal sensitivity towards the short wavelengths when the eye adapts itself to reduced illumination; the shift seems paradoxical, since twilight and moonlight are, on the contrary, richer in long than in short wavelengths. In the sea, on the other hand, it is quite understandable: when fish swim downwards, the light diminishes, and at the same time becomes richer in short wavelengths, because of the maximum transparency of the water in the blue-green region. In air-breathing mammals like human beings, the Purkinjee effect may be a throw-back to remote aquatic ancestors.

## LIGHT AND DEPTH

The question is often asked: To what depth does light penetrate in the sea? Before an answer can be given to this question, a brief explanation of the problem is necessary.

Even within the visible spectrum, the various radiations are absorbed unequally. Far from the shore water is most transparent, for a wavelength a little under 0.5$\mu$, in the blue region, but in coastal waters pigments in suspension often cause this maximum transparency to be shifted towards the green.

During the *Albatross* expedition led by Pettersson in 1948, Jerlov carried out many meticulously controlled measurements of oceanic transparency, using photo-electric photometers equipped with filters isolating narrow spectral bands. In the purest seas, like the Sargasso Sea or the eastern Mediterranean, the waters far from the coast reach maximum transparency towards 0.47$\mu$; in this spectral range, the sea is astonishingly clear, almost as transparent as distilled water.

If light in the sea were subject only to true absorption, that is, a transformation of a fraction of radiant energy into heat, the law of the diminution of light would be a decreasing exponential function of depth, since layers of water in arithmetical progression would absorb radiation in accordance with geometrical progression, and each fathom of water would stop the same percentage of the energy which reached it. But in addition to true absorption there is diffusion, which scatters light in various directions without transforming it into heat; it is not lost, but deviated. Hence the law of diminution is no longer exponential, nor would it be even if we suppose the properties of sea-

water at any given depth to be constant (and such a supposition can, of course, only be accepted as a general approximation). Theory and experience both indicate that beyond a certain depth, about one hundred metres (or fifty fathoms) in clear water, an approximate exponential decrease is found which makes it possible to state a fairly regular absorption factor per metre; its minimum value is about 3 per cent (for distilled water it would be 2 per cent, i.e., practically the same).

We are now in a position to answer the question: At what depth is daylight still visible? Strictly speaking, the amount of energy tends towards zero as depth increases, but in an asymptotic curve; the depth at which sunlight is still detectable will thus be limited by the sensitivity of the receiving apparatus employed. It is calculated that with the most sensitive emulsions now known, and at an exposure time of about one hour, some darkening of a photographic plate could be recorded at depths of about seven hundred metres, that is, of course, in the clearest seas as mentioned above. Under the most favourable conditions, the human eye could perceive a glimmer of light even slightly further down. (Near Bermuda, Beebe was still able to see at about six hundred metres, though conditions were probably not at their best; all that penetrates, of course, is a narrow band in the blue wavelengths—the maximum domain of transparency, as we have already seen.) With an electron multiplier, the most sensitive receiving apparatus now in existence, it would be possible to go down to about one thousand metres (five hundred fathoms).

These are naturally theoretical limits, and in most seas the actual depths would be far less; moreover, marine creatures generate, by animal phosphorescence, a light which soon becomes more intense than the vestiges of daylight. Houot and Wilm, the first bathyscaphe explorers, were spellbound by the entrancing luminosity of the great ocean depths; in order to take advantage of this luminosity, deep-sea fish often have enormous eyes, as large as a man's for a body only about eight inches long.

### ULTRA-VIOLET RAYS

Ultra-violet penetration in the sea is a problem of special interest to biologists. Some of them share the belief of Bernal that it was the cause of life. They assume, by analogy with the other planets of the solar system, that the original atmosphere of our globe consisted mainly of hydrogen, methane, ammonia and hydrogen sulphide, and that the gradual solidification of the earth's crust released carbon dioxide, while the hydrogen slowly evaporated into interplanetary space. The oceans would then have contained ammonium carbonate and ammonium sulphide in solution; and by means of these chemical bodies, short-wave ultra-violet solar radiations, then very intense, would have been able to produce a synthesis of the nitrogen compounds which, by polymerization, supplied the matter for organic substances. These products, in low

concentration at first, would have settled and accumulated in the clay deposits along the sea coasts.

Since that remote era, these ultra-violet solar radiations have ceased to reach the earth's surface. It appears that assimilation by the chlorophyll-containing cells of green plants under the effect of sunlight gradually removed almost all the carbon dioxide from the atmosphere, replacing it with oxygen and thus constituting the air as we know it. In the upper atmosphere, part of this oxygen is transformed into ozone, creating an opaque barrier against far ultra-violet radiation of solar origin, which, though necessary to the beginnings of life, is believed to have become highly dangerous for organisms at a more advanced stage of evolution.

The sea's transparency to present ultra-violet solar radiations is a problem which long remained obscure. The first experimenters, about 1930, described a quasi-opacity which was subsequently challenged. The question was re-examined by Jerlov, who used selenium cells with special filters; measurements were limited to the surface layer of water (down to 15 metres) of the western Pacific and the Mediterranean. For ultra-violet radiation bordering on the visible spectrum (0.37μ), a good degree of transparency was indicated (absorption of only 5 per cent per metre). The transparency only diminished slightly with the shorter wavelengths: at 0.31μ, i.e., at the end of the solar spectrum receivable on the earth's surface (wavelengths beyond this range being stopped by ozone in the stratosphere), absorption was still not more than 14 per cent per metre. It is true that these measurements were made in very clear seas. According to Kalle, absorption in the Skagerrak reached 90 per cent per metre for this same wavelength, perhaps because of a coloured pigment due to the sea-weed along the coast. Similar differences were recorded by J. Lenoble (1954-57) by means of a particularly accurate method, involving the use of a quartz spectrograph in a water-tight container, operated by remote control. At a wavelength of 0.35μ, for example, absorption per metre was about 15 per cent in the Mediterranean and 40 per cent in the English Channel.

These results show that, in clear waters, ultra-violet solar radiations penetrate with appreciable energy down to a maximum depth of about fifty metres. Ultra-violet rays are also biologically important for the fixation of calcium by means of sterols produced in the epidermis of land-dwelling creatures by ultra-violet radiation; insufficient irradiation can cause rickets. In marine animals the calcium-fixation process is obviously different, but it is possible that, near the surface, ultra-violet radiations may be a factor of some consequence.

### LIGHT AND PRODUCTIVITY

These questions of the transparency of the oceans, both in the visible and the ultra-violet regions of the spectrum, are important not only for physicists, whom they help to ascertain thermic conditions in the sea—that gigantic heat regulator controlling our planet's temperature—but also, and perhaps

even more so, for biologists. The sea's capacity to produce organic carbon by photosynthesis is a phenomenon of vast proportions, as measurements obtained by means of techniques involving the use of radio-activity (in particular, that of carbon 14), have recently shown; it is now an accepted fact that every six or seven years, each molecule of carbon dioxide in the atmosphere re-enters, either the terrestrial or the marine life cycle, the probabilities in favour of the latter being two to one.

Productivity is by no means constant at all parts of the ocean's surface. Marine deserts like the Sargasso Sea exist, where productivity per square metre is three times less than the average; there are also super-productive Edens, like the current along the east coast of Africa. These differences have not yet been satisfactorily explained, and transparency is only one of the factors involved. In any case, the immense reserve of life, and consequently of possible food for humanity, which the oceans represent is directly dependent upon the penetration of sea-water by solar energy.

## SCATTERING

In addition to the true colouring matter mentioned above (doubtless of biological origin, since salts dissolved in sea-water are transparent in the visible spectrum, and only in the ultra-violet region do calcium and magnesium ions show a certain absorption capacity of their own), sea-water contains a great many scattering particles of various origins: near the coasts, terrigenous deposits and slime which contaminate shallow seas like the English Channel or the North Sea; everywhere, colloidal micellae or larger particles (iron hydroxide, in particular); and, lastly, living cells constituting plankton, which is so abundant at times that, under bathyscaphe searchlights, at certain depths, it looks like a profusion of fine snowflakes.

All these particles play a vital part in marine optics; like mist or fog in the atmosphere, they scatter light in all directions. But is should be remembered that there is an essential difference between air and water. In fine weather, when the air is very transparent, there is still a considerable amount of scattering due to the air molecules themselves, which, as Rayleigh was the first to point out, are responsible for the blue of the sky. This is because particles which, like oxygen and nitrogen molecules in the atmosphere, are very small compared with the wavelength of the light, scatter it in inverse ratio to the fourth power of the wavelength; the blue of the spectrum is therefore scattered far more than the red, and the sky appears particularly blue when this molecular scattering is the only one involved. The air, even in fine weather, contains water molecules in tiny drops, and the blue is then washed with white; when these drops reach a size approaching that of the wavelength (as in mist and fog), all the blue disappears; the light is scattered almost independently of its wavelength, and therefore remains white.

But in the sea, in a manner of speaking, the weather is never fine. Molecular diffusion (caused in this case by the water molecules themselves) still exists and follows Rayleigh's law (scattering inversely proportional to the fourth power of the wavelength); but it is completely negligible compared with the other forms of scattering due to floating particles. A simple calculation shows that, if molecular diffusion were the only type of diffusion taking place in the sea, the latter would be amazingly transparent (a depth of nearly one and a quarter miles would have to be reached before the energy of the middle of the visible spectrum was reduced to one-tenth of its value at the surface!).

Microscopic examination of sea-water samples reveals that most of the particles in suspension in the sea are less than 2.5μ in diameter. They cannot, therefore, be grains of sand, air bubbles or plankton, but might perhaps be very finely divided clay or various types of colloidal micellae. Rayleigh's law then no longer applies, of course: as soon as the diameter of the particles is equal to half the wavelength, the exponent falls from 4 to about 2; in the case of the comparatively large particles already mentioned, selectivity no longer exists (exponent zero), that is, the effect is exactly the same as that of fog in the atmosphere.

Particles in suspension in the sea are of interest to oceanographic physicists because of the optical diffusion which they produce; but biologists are also concerned with them, because the production of living matter and the fertility of the sea depend upon the nature of such particles and their abundance. These problems have recently been the subject of many studies, involving the use of a variety of techniques which I should like to describe briefly.

The most direct method is obviously to collect water samples at a specific depth, by means of the usual bottles, and then to filter the water and examine the residue. As filters, Atkins and his associates used collodion membranes with pores about one micron in diameter; the weight of the residue, after drying and calcining, ranges, according to the purity of the water, from a fraction of a gramme to a few grammes per cubic metre of sea-water. The content is usually highest near the surface, sometimes at about twenty-five metres; seasonal variations, related to the development of plankton, also occur.

Another more complicated process is to measure the Tyndall effect—that is, the amount of light scattered—on water samples brought aboard the oceanographers' ship. This technique, first used by Kalle, has been more closely defined in many respects by Jerlov. It is important, especially with clear water, to avoid parasitic contamination which would distort the results; moreover, the measurements must be taken as quickly as possible after the sample has been brought up, so that bacterial processes do not have time to modify the specimen's limpidity.

Jerlov observed that, in these circumstances, the Tyndall effect varied only slightly with the wavelength: scattered light is scarcely more intense (5 to 10 per cent only) in the blue region than in the red, which confirms the large

size of the particles in relation to the wavelength of the light. He also noticed that the content of matter in suspension gave different waters an individuality which could be traced for long distances; for instance, in samples taken from the depths of the Atlantic, Mediterranean water which has flowed through the Straits of Gibraltar is plainly recognizable.

The depth distribution of matter in suspension depends on many factors. Since much of this matter is of biological origin, it must have come into being in the photic zone near the surface, where the intensity of the light is favourable to life. Once dead, this waste matter sinks slowly—although less slowly when the water temperature is higher, since the viscosity which impedes it diminishes as the temperature rises. Obviously, where there are vertical water currents, they have an important effect on the process. Consequently, depth measurements of the distribution of particles under equatorial currents reflect fairly accurately the eddy movements caused by these displacements of water. Sometimes local points of maximum turbidity are detected in the depths—real submarine clouds shifting with the local currents. They are of uncertain origin but may have considerable biological importance because, in deep seas, particles in suspension act as nuclei for the absorption of phosphates, on which the fertility of marine life depends. Radio-active substances also seem to be attracted to this matter, by which they are adsorbed. At a recent congress at Monaco, attention was drawn to the dangers of contaminating the sea with atomic waste and, in this alarming phenomenon, matter in suspension plays a predominant part.

Still another technique for studying particles in suspension consists in operating on the spot by lowering measuring apparatus to the depth to be studied. All the disadvantages inherent in the taking and drawing up of samples, with the risk of their being modified by bacterial processes, are thus avoided. In 1934, Pettersson built an ingenious apparatus for measuring scattered light by means of matter in suspension; this apparatus, which could only be used at night, consisted of a lamp and a photo-electric cell in the same water-tight container; it was able on occasions to detect an extraordinarily fine stratification, turbidity maxima being sometimes only a few decimetres thick. Ivanoff recently constructed a submarine photometer which measures the Tyndall effect on the spot and can be used even in broad daylight. Such techniques for the measurement of matter in suspension will no doubt be employed on an increasingly large scale.

## SUBMARINE LIGHT

Since true absorption and scattering are found together, the problem of light distribution in a submarine 'fog' is a surprisingly difficult one.

Computations at once become extremely complex. The sea being a highly turbid medium, multiple scatterings must not be left out of account, i.e., rays

which have changed direction several times between their entry into the water and the moment when they reach the observer. It is also necessary to know what physicists call the 'scattering diagram', representing the way in which light diffused by a particle is then spread through space, scattering its energy in various directions; for particles which are small in comparison with the wavelength, this diagram is known, and is known to be symmetrical as much light is scattered behind as ahead, and half as much at right angles to the incident direction. With large particles, the problem becomes more complicated; the diagram could theoretically be calculated, by means of Mie's electromagnetic theory, if the diameter of the particles and their refraction index were known. The results of this theory have been set down in numerical tables, thanks to electronic computers which shorten an elaborate process of calculation. But particles in the sea are not necessarily spherical, and they have a whole range of different diameters.

Last but not least, the integral equation which would determine the distribution of light can be solved only by approximations. An ingenious method devised by Chandrasekhar has been applied to the sea by J. Lenoble who, in comparatively simple cases, has managed to carry out computations to approximate results that are accurate enough to be compared with experimental data; in a homogeneous sea, a balance would be reached at a certain depth; that is, the angular distribution of energy would have a fixed relative value which would remain the same even farther down (although energy would, of course, diminish in absolute value with increasing depth). We now seem to have discovered the right method of solving these difficult problems of propagation in turbid seas; with the help of modern computers, it may, at least in principle, be possible to predict all submarine optic phenomena, provided that the physical parameters (true absorption, scattering and scattering diagram) are known at every point and for every wavelength, and also the conditions at the limits (lighting at the surface of the sea, and properties of he bottom).

For the time being, however, it is better to rely still on experiment. A few optical measurements have been taken in submarines and bathyscaphes, but a more satisfactory solution is to send down submarine photometers; results are sometimes recorded in the apparatus, but more often transmitted to the ship by an electric cable. As mentioned earlier, the receiver now most widely used is the photo-electric cell with amplification in the cell itself by multiplication of the photo-electrons. An instrument of this type was built by J. Lenoble in connexion with the International Geophysical Year. In the sealed container, small motors controlled by the cable from the ship make it possible to interpose neutral absorbents in front of the cathode of the cell—to ensure optimum operating conditions—and also a narrow band-pass interference filter chosen from a set of 16 filters covering the whole visible spectrum and the beginning of the ultra-violet (the infra-red is of no importance, since it is stopped by the first

few decimetres of water at the surface). With this kind of apparatus, maximum transparency in pure waters out at sea is, as already stated, found to be at about 0.47μ; towards the coast, the maximum is shifted towards the longer wavelengths, sometimes as far as 0.53μ; it is also possible to measure scattered light returning towards the surface and the directional distribution of light at any depth.

## THE COLOUR OF THE SEA

Molecular diffusion explains the blueness of the sky, and many people think the same is true for the sea. But the assumption is by no means reliable. The problem is, in fact, twofold. The colour of the sea as it appears to an observer in the air is the result of two factors: first, the light reflected on the surface of the water, coming from a blue or cloudy region of the sky; and secondly, the diffused light coming up out of the water. The latter is the only light perceived by a man who floats on the surface and looks down into the water through diving goggles, and it is to this light that our observations will be confined.

It is easy to demonstrate that, if there were only molecular diffusion, and if multiple scatterings could be left out of account, a deep sea would be colourless. True absorption and multiple scatterings complicate the problem, but it seems that the blueness of the open sea is mainly due to the true absorption of long wavelengths by the water (even when it is pure). This therefore seems to be an entirely different process from that which produces the blueness of the sky. The sky is blue rather as cigarette smoke is blue, through the interposition of very small scattering particles; the sea is blue like fountain-pen ink, because the red is retained and transformed into heat.

Near the coast, yellow substances in solution, probably derived from seaweed, turn the blue to green; this is particularly striking off the coast of Brittany. Lastly, matter in suspension may sometimes change the colour of the sea, making it look yellowish, milky or even red. Certain micro-organisms or other colouring elements may contribute to this; for instance, in certain red waters of Florida, Collier has drawn attention to substantial titanium and zirconium content, obviously related to the dissolving of coloured coastal rocks.

## OPTICAL CHARACTERISTICS OF VARIOUS WATERS

For a long time, oceanographers have distinguished sea waters by their temperatures and salinity (content in dissolved salts, of which most abundant is, of course, sodium chloride). In the past few years, experiments have also been made to determine their content in isotopes (deuterium, oxygen 18, etc.). However, such measurement is a delicate matter and requires costly apparatus such as the mass spectrograph. It has often been wondered whether transparency and diffusion properties also might not enable the source and movement

of ocean waters to be determined. We have already seen how the study of changes in turbidity due to environmental conditions afforded a means of measuring turbulence and vertical displacements. The German oceanographer, Joseph, believes that the range, limits and movements of various waters can also be defined by studying water absorption, provided that the study is sufficiently extensive and general; optics, combined with conventional hydrology (temperature and salinity) may give us more specific knowledge about the difficult problem of the transport of ocean waters by currents. The importance of such transport at the surface has always been recognized; but interest has now extended to deep currents, since considerable movements of water at great depths have been detected.

Quite recently, another optical property of submarine light has been proposed as a means of identifying water masses, i.e., the stage of polarization of the light. It has long been known that light from a blue sky is polarized in a rectilinear and partial manner; submarine radiations from the sky must therefore, in these circumstances, be partially polarized; in addition—and this will occur even when the sky is completely overcast—light is polarized by diffusion in water. Hence we have a complex combination of phenomena.

Ivanoff, who has been studying the problem for some years, first measured the general effect by a photographic method involving the use of apparatus set into operation by a diver; the first results, obtained near Corsica, indicated strong polarization in clear water. In order to extend the measurements to greater depths, where diving was no longer possible, Ivanoff constructed a photo-electric device which he used off Bermuda, where he was working with biologists interested in polarized light (for it would appear that some marine species use the polarization of light as a compass, just as bees do). Generally speaking, polarization increases with the water's limpidity, and it seems to be the most sensitive physical criterion for the measurement of limpidity. It is possible that an 'optical' diagram, of which the variables would be the absorption and polarization of light in water, could be used, like the conventional temperature-salinity diagram, in order to distinguish a particular type of water.

## VISIBILITY OF IMMERSED OBJECTS

Having thus considered the principal data relating to marine optics, we will now review its main practical applications.

The first is connected with the visibility of an immersed object from the air (ship or plane). This basically military problem has given rise to much research, with rather disappointing results. The depth of visibility obviously depends on the limpidity of the water, and has even supplied the oldest and simplest means of measuring transparency (Secchi's disc). But no artificial device can really alter natural visibility. The submarine object can, of course, be slightly

camouflaged with blue-green paint or made more visible by bright, pale yellow-orange paint contrasting with the blue of the water (aviators' parachutes, hydrographic bottles and other equipment are so painted). But all that has little effect.

We are also helpless when faced with the problem of the diver's short range of vision. The old engravings which we admired as children, with Captain Nemo in a diving suit contemplating vast submarine panoramas, have unfortunately proved to be mere fantasy; what really exists is a blue fog, a luminous wall blurring all details 15 metres away. No polarizing or coloured filter can dissipate this mist. In land fog, a few 'windows' stay open in various infra-red regions; but not here, since water absorbs infra-red rays. A diver who lights his way by taking down lamps is merely worse off, like a motorist in the fog who sees less with his headlights than he would in daylight. Nothing can be done about it, because diffusion in the sea has practically no relation to wavelength. A submarine looking for the enemy will therefore not see him with visible light, any more than with the electromagnetic waves of radar, which are quickly absorbed; the only instrument it can use is a sonic one, or rather, supersonic, for elastic waves can travel hundreds of yards, even miles, in the water. And so the ocean depths are sounded by measuring the time-delay of the returning echo of such vibrations, which are far less subject to absorption by water than light.

Theoretically, however, there is an optical solution, but it is one which our present technical resources do not yet enable us to apply. Supposing that a submarine sent out extremely brief flashes of light, of a thousand-millionth of a second in duration, for example—which is not beyond the realm of possibility—then each flash propagated in the water would light only a section a few decimetres wide; light reflected on an obstacle would therefore return to the observer with an appreciable time-lag compared to that of the light scattered by the layers of water between the observer and the obstacle. Thus, if the observation were made through an obturator which also opened for a thousand millionth of a second only, scattered light and significant light could be separated. For the moment, this is only a dream, but it is perhaps not so very far from becoming a reality.

## SUBMARINE PHOTOGRAPHY

During the last war, the transparency of the sea was found to be useful in connexion with an interesting method of measuring shallow depths near the coast by aerial photography. A landing was being prepared, not on the French coast, for which there are excellent maps, but in the Far East, where the seaboard is comparatively unknown and where landing craft might have run aground too far from the shore. The plane, at an altitude of about 1,500 metres, vertically photographed the beach with two identical, synchronized cameras,

one with a green and the other with a red filter. A simple and sufficiently accurate general correlation of absorption by the sea-water of the two types of radiation which pass through these filters gave the depth of the sea, by means of simple measurement of the photographic darkening on the two plates. The need for two different photographs may be explained by the fact that the screen effect produced by the water between the observer and the sandy bottom depends on two variables: the thickness of the water and its absorbent properties. Two measurements are thus needed in order to eliminate this second variable and find the depth. The method is quick, but of course can apply only to depths of 10 to 15 metres at which the sea bed is still visible; its accuracy is about 10 per cent. The technique might be useful for rapid surveys of gently sloping coasts and for the study of sand movements.

Real submarine photography, with underwater cameras, is not new, since, as long ago as 1893, Boutan obtained very good photographs at Banyuls with a camera inside a sealed container. Since the last war, the extraordinary development of diving, either as a sport or for more technical and scientific purposes with the self-contained diving-suit, has led to the production of quantities of sealed containers facilitating photography. In broad daylight, without any artificial lighting, it is possible to photograph in black and white down to 50 metres, with an exposure of 1/50 sec. and an aperture of f/3.5; colour photographs can be taken at a depth of some thirty metres with an exposure of 1/25 sec. and the same aperture. The only optical peculiarity of such photographs is the fact that the refractive index of water (4/3 as compared with 1 for air) enlarges the image in proportion, the angle and depth of the picture being correspondingly reduced. This is an annoying complication, because light diffusion in water, by blurring the more distant planes, prevents the photographer from getting far enough away from his subject, thus forcing him to use the widest possible field. The remedy is to use a special corrective window instead of flat glass, so that both field and size are represented as in the open air.

Submarine colour photography in daylight is rather disappointing. Reds, oranges and yellows disappear at a depth of ten metres or so, and everything is a uniform blue-green. One might just as well photograph in black and white and give the result a blue-green tint afterwards. But artificial light reveals an extraordinary richness of colour in the submarine world. The inventors have really let themselves go and have produced apparatus of all kinds—incandescent lamps and electronic or chemical 'flash' devices. With this wide variety of equipment, submarine photographers can satisfy all their ambitions.

For biologists, submarine macro-photography, i.e., photography at very close range in which all details appear, is a remarkable method of working and obtaining documentation. A problem has arisen out of the wealth of colour discovered in this way. It seems paradoxical that nature should have so richly adorned animals and plants living permanently at a depth where

only blue-green rays of daylight can reach them. What is the use, for example, of such magnificent bright reds which no eye had ever beheld before men brought artificial light to these depths?

While it is pointless to seek at all costs a teleological explanation of nature's caprices, the following answer might be given. The resemblance of the colour of animals to the colour of their surroundings is a well-known defence against their enemies. But such homochromy is difficult to achieve in the case of air-breathing creatures because they must match both the hues and the brightness of their background; whereas, in the sea, the problem is simpler, because only brightness counts and, since the question of colour is no longer of any particular consequence, nature can allow herself a wide range of pigments. In short, the splendid colours of the submarine world probably exist because they are not dangerous; but on land or in the air, such a wealth of colour might have led to the extinction of these excessively beautiful creatures.

Submarine photography can, of course, be supplemented by cinematographic records; the problems are the same, except that sealed containers for motion picture cameras are more voluminous, and more lasting sources of artificial light are required. Commandant Cousteau's magnificent films are so well known that it is unnecessary to dwell on the instructive and artistic merits of this new world now open to the human race—a world of silence and mystery, where weight is non-existent and where we can, far more easily than in the air, fulfil Man's age-old dream of moving in three dimensions instead of remaining glued, in accordance with Newton's law of gravitation, to the surface of the earth.

## AUTOMATIC PHOTOGRAPHS

Below a depth of about fifty metres, the diver must be replaced either by a bathyscaphe, with which some fine photographs of great depths have been obtained—showing mysterious views of the submarine 'mole hills' inhabited by we know not what living creatures—or by an automatic camera let down at the end of a cable. The automatic camera photographs blindly whatever is there and is, of course, lighted artificially. In the United States of America, Eggerton has invented cameras which resist the greatest deep-sea pressure and also indicate, by a supersonic signal, the distance between camera and the sea bed. In this way, one can be sure of stopping a few metres from the bottom. But the results have been somewhat disappointing, for, out of tens of thousands of pictures, very few have shown a fish. Yet we know that these depths are populated, probably less than near the surface, but nevertheless fairly densely. The phenomenon is understandable if one imagines what the result of the same experiment would be on land. A camera approaching the ground suspended from a balloon or a parachute would certainly put cattle, game and even human beings to flight; and the pictures taken would give the impression

that the land was practically uninhabited. Marine animals are no doubt particularly sensitive to elastic vibrations in liquid, and the clicks of the Eggerton apparatus announcing the bottom must scare them away. For geologists, on the other hand, photographs of the bottom of the sea, taken under kilometres of water, are a marvellous source of documentation. They often show, for instance, 'ripple marks' like those on the sands of tidal beaches. These ripple marks used to be attributed to surface agitation, but, since the latter obviously cannot exist at such depths, they must indicate deep water currents which provide one of the arguments in favour of regular movement in the deeps, quite other than the slumbrous tranquillity formerly postulated.

Commandant Cousteau has recently perfected another ingenious automatic photographing technique. It consists of a submarine sled, a kind of *troika*, which can be towed at the end of a cable by a ship, even at a depth of several hundred metres; on the sled is a motion camera, synchronized with an electronic flash which emits 24 flashes a second. The films taken—some of which were presented last September at the first International Oceanographic Congress in New York—are highly impressive; one really feels as if one were being borne by the sled through the magic world of the great ocean depths.

As stated earlier, ripple marks supplied the first proof that the deeps were not a motionless, half-dead universe. The creatures fleeing before the *troika* are added proof. And then we notice that the ocean floor is often not the dreary stretch of mud we had expected; many small pebbles are scattered over it. Where do they come from? Some may have been brought by currents, such as those occasionally created by earthquakes. These 'turbidity currents' are real submarine torrents, sometimes flowing as fast as 15 knots, sweeping down slopes and causing erosion where they have passed. Moreover, stones are constantly raining down upon the sea: about three thousand tons of cosmic spherules fall into it every year. These iron and nickel meteorites have greatly intrigued submarine geologists; the phenomenon already existed in the Tertiary Era, but seems to have become far more extensive since the last Ice Age.

### ECOLOGY AND PHOTOGRAPHY

The marvellous tool provided by photographic and film techniques, besides being used for physics research, has recently become a boon to oceanic ecology. Professor Drach at Roscoff, for example, has used both self-contained diving-suit and colour macro-photography methods to collect ecological documents of untold value, which can afterwards be used in the calm of the laboratory, to study the population of the coastal submarine area. Research of this kind cannot of course be extended beyond a depth of some forty metres. Further down, in order to make a scientific survey of the continental shelf, which goes down to about two hundred metres, Commandant Cousteau has devised a very handy little submarine, the 'diving saucer'. An observer sitting beside the

pilot is able, at leisure and with the help of projectors, to study and photograph the vegetation and environmental conditions in a sphere of which we still know so little and which may represent Man's reserves of food in the future.

TELEVISION

Another method of seeing what happens under water without going down oneself is to lower a television camera with the necessary lighting units. This technique is of course rather more difficult than photography, if only because the image must be relayed from the depths to the ship by means of a coaxial cable. The first experiments date from the atom bomb explosion at Bikini, some years ago. Obviously, divers could not be sent down into the atoll's waters, which were contaminated by radio-activity; and so submarine television cameras were used to replace the human eye in exploring the underwater effects of the explosion.

Since then, the use of submarine television has spread to such a point that it is now employed in public works projects, such as the building of dikes or other constructions in the sea. But so far its scientific contribution to oceanography has been slight.

It may, however, have a big future ahead of it. For instance, there has been much talk recently about drilling through the earth's crust at depths of several kilometres of water. For isostatic reasons, this sedimentary layer is far thinner under the ocean than on dry land. It might be possible for drilling to reach the interior of the globe and enable geologists to know for certain what the inside of our planet is made of. (Our only tool at present is the sort of auscultation which can be carried out by means of seismic waves, but the data thus obtained are indirect and hard to interpret.) The great strides made in deep drilling by the petroleum industry would indicate that this project is not so fanciful as it might appear. There are still, of course, considerable difficulties to overcome, to mention only that of immobilizing the ship from which the work is to be done. Submarine television would probably be of great use in beginning the drilling operations and in seeing what is being done on the ocean floor.

Some oceanographers have wondered whether the applications of submarine television could not be extended if light waves were replaced by some other form of radiation better able to penetrate through ocean water. The sea, as we have said, is terribly absorbent for all electromagnetic waves, and its opacity is the main reason why our knowledge of the seas is not more advanced. (If the atmosphere were opaque, science would doubtless be entirely different, if only because astronomy, the mother of the exact sciences, would be no more than starting, via radio-astronomy!) But there is one form of energy that penetrates through water relatively easily: the elastic vibrations of sonic and supersonic waves. Hitherto, they have scarcely been used except for sounding

and direction-finding by means of sound channels, but their applications could certainly be extended.

A start has already been made on the study of marine sediments by means of extremely short supersonic 'pips', the spectrum of which is fairly wide, i.e., it includes quite a wide group of frequencies (it is a 'noise' and not a pure sound). By analysis of the echo in relation to the wavelength, it is easy to detect the reflection of high frequencies at the point where the water meets the sediment, and that of the low frequencies which penetrate the sediment to varying depths before returning. But it might be possible to do better still and sweep the sea bed with a narrow supersonic beam, analysing, by a technique similar to television, the image thus received. There would be projected on a screen a kind of acoustic image of the bottom, the 'colour' of which would change according to the hardness and thickness of the sediment. The technical drawback to this method is of course that acoustic wavelengths are comparatively long, especially when the aim is to traverse a considerable thickness of water; consequently, optical apparatus—lenses or mirrors—intended to concentrate the energy of a particular radiation must, in order to be effective, be large enough to cover a great many wavelengths. This would make them cumbersome, but the difficulty is not perhaps impossible to overcome.

## DEEP SCATTERING LAYER

A problem which seems to involve oceanic transparency is that of the famous DSL (deep scattering layer) discovered during the last war by supersonic sounding apparatus. In an ocean one or several kilometres deep, a parasitic echo is observed, usually at a depth of 300 metres, or as much as 500 metres in very clear waters. This layer rises towards the surface at dusk and sinks back to its original position at daybreak. This daily movement suggests a biological origin, the presence of organisms whose migrations are related to the penetration of the sun's rays and which accumulate at a fixed depth, in sufficient quantity to produce an echo by partial reflection of the supersonic waves. But this daily movement is not in itself enough to prove that the layer consists of living organisms; for in the upper atmosphere, there are daily movements of the ionized layers governing the propagation of electromagnetic waves, and this phenomenon is purely physical. However, dredging has corroborated the biological explanation of the DSL. Moreover, light-sensitive receivers have been lowered to that level during the night, and a biological emission of light is observed, revealing a great density of life in the layer.

## MISCELLANEOUS APPLICATIONS

In this article, we have reviewed the scientific and technical applications of marine optics. It now only remains to deal with what happens at the surface, where the sea meets the atmosphere, for here, too, optics play a part.

Light reflection at the point where air meets water is the reflection well known to photographers, since it enables them to produce their famous back-lighting effects; but a scientific study of these reflections is not lacking in interest and reveals a fairly simple method of studying the movements of this surface and dividing them into their temporal component parts, in other words, of analysing what oceanographers now call, by analogy with optics, 'the sea-level spectrum'. During the last war, British physicists, and particularly Longuet-Higgins, took up this old problem, and light reflections on ripples and waves supplied them with very interesting data. It is common knowledge that surface agitation of the sea depends on the wind and on the surface tension. The latter phenomenon varies considerably from point to point, because of a film of sometimes mono-molecular organic matter which spreads over the surface and produces flat, unrippled areas of the sea; everyone has observed them in calm weather.

A similar problem is the loss of energy at the surface. An appreciable fraction of radiation from the sun and sky is stopped by the first decimetres of water. There is no mystery about this in the case of infra-red rays. But within the visible spectrum, the cause is not really understood. Foam, air bubbles transforming the surface area into a milky emulsion and any number of other reasons have been suggested. In fact, we still do not know what the exact answer is.

At the end of an article with a title which no doubt suggested to the reader that only a narrow field would be covered, we should perhaps conclude by confessing our ignorance in many spheres of oceanography, and especially in the study of radiations. In July and August 1960, the International Association of Physical Oceanography is to organize, under Unesco's sponsorship, a symposium in Helsinki on radiant energy in the sea. This shows that, despite rapid progress in recent decades, largely through technological development, much remains to be done in this field. International collaboration is urgently needed in order to speed up our advance towards greater knowledge of the whole sphere of submarine light, which is so important for the ecology and even the economy of our planet.

# HYDROPSIS: ITS SCIENTIFIC BACKGROUND AND APPLICATION

## In navigation, fisheries and meteorology

*by*

T. LAEVASTU

*T. Laevastu is a member of the Fisheries Biology Branch of FAO and has specialized in fisheries hydrography and chemical oceanography. His earlier work concerned, in addition to several extensive studies of trace elements in the sea, a variety of other oceanographical subjects, from extra-terrestrial material in deep sea deposits to the ecology of Atlantic salmon. He is author or co-author of a number of reviews on regional oceanography, plankton and benthos.*

### INTRODUCTION

As in all human activities, man's sailing of the seas and his use of marine fishery resources require, for safety and success, the ability to predict the behaviour of winds, waters and living organisms.

This ability to predict, which, of course, is one of the primary aims of science in general, is made possible by the application of descriptive and experimental procedures to natural and artificially established systems, and by the interpretation of vast arrays of data gathered in the field and laboratories. Only after such description, analysis and interpretation can relations be recognized and prediction systems developed. For the seas, this task of description, analysis and interpretation is a vast one which now, after more than a century of work, is leading to the stage of prediction. At present only limited predictions can be made but it is clear that oceanography will in the future develop along the lines of meteorology, with an applied branch of routine observing and forecasting and a branch of basic research.

To designate synoptic oceanography, which is the task of the applied branch, Lyman proposed (in correspondence) a single word, *hydropsis* (hydro synopsis), roughly comparable with synoptic meteorology. Hydropsis may be defined as the reduction and interpretation of data, from a few days' observations but referring to more extensive sets, on conditions in particular areas, presenting such predictions as the data permit, of conditions likely to prevail in the immediately following period. In sentences, the word should be used as the expression 'synoptic meteorology' is used. The adjectival form is 'hydroptic'. Primarily, hydropsis will deal with the thermal structure and dynamics of the ocean. Lyman also suggested the term *hydroclime* to indicate average hydro-

graphical conditions, based on statistical treatment of, for example, monthly data collected over many years.

Forecasts have long been made, sometimes with considerable success, of oceanographic phenomena, such as tides and waves. In recent years attempts have been made to extend forecasting to other phenomena, and in this article an account is given of some of this work. The article deals mainly with the upper layers of the oceans, because the changes in physical-chemical conditions in the deeper layers, below 200 metres, are relatively small and predominantly slow. These conditions, which are usually influenced by those at the surface, influence man's activities only in very special cases. But it must be stressed that basic knowledge of the deep sea is, in the long view, as important as that of the surface waters for an understanding of the complicated interactions in the sea.

## WHAT TO FORECAST IN THE SEA

Whilst complete understanding of natural processes and ability to forecast all phenomena is an aim of science, for practical and economic reasons, research programmes in practical fields must be limited to prediction of those phenomena that directly affect the activities of man. Moreover they must be confined to the investigation of easily observable and measurable elements whose relations with the phenomena to be predicted can be clearly demonstrated.

The oldest subject of prediction in the sea has been tides. Although the methods of tide prediction in coastal areas have been perfected to the smallest detail, there is still no good method applicable to off-shore areas; yet the prediction of tidal currents and times of slack water is also needed there. Tides cause fluctuations in the depth of the thermocline (the layer in which temperature changes relatively sharply with depth). Tidal currents affect navigation and the use of fishing gear, and periods of slack water and also of vertical oscillation determine the behaviour (e.g., shoaling and vertical migrations) of pelagic (surface-dwelling) fish. The features of the off-shore tides of a particular locality which it is most useful to predict are (a) the times of slack water and (b) the maximum speeds of tidal currents.

Wave forecasts are used in navigation for the choice of 'least time tracks' and to increase safety and comfort at sea. Wave data are also used for the determination of the average depth of the layer of mixed surface water. There are at present several formulae for wave forecasting, each differing slightly from the others, although they could easily be combined. The main wave feature to be forecast is significant height (the average height of one-third of all waves in a wave spectrum) which should be related roughly to such features as other height characteristics and wave lengths. Simplified formulae for the forecasting of swell (the long waves generated by distant wind and storms) have yet to be established.

In the past, relatively little attention has been given to the prediction of real surface currents, although much theoretical work has been done on the big current systems. Knowledge of surface currents is used in navigation, but is still more important in fisheries and for forecasting the actual temperature structure at a particular locality and meridional transport of heat.

Currents are of various kinds and origins. Tidal currents have already been mentioned above. The major currents of the ocean—the so-called permanent currents—are caused chiefly by differences of sea-water density. These currents have seasonal variations, caused by seasonal variations in density distribution, and in the intensity of the other driving forces of these currents—the wind systems and heat exchange distribution. These seasonal changes can be predicted some weeks ahead by the use of meteorological and oceanographical data. Finally, superimposed on the tidal and permanent currents are wind currents which, carrying on from day to day, must be predicted from the wind data.

The features of currents to be predicted are: (a) for tidal currents—maximum speed, dimensions of tidal ellipse, and direction of rotation; (b) for permanent currents—direction and speed; (c) for wind currents—direction and speed at given wind, direction and direction of rotation, and changes in speed in response to changes in wind.

Since temperature is one of the most easily measured environmental factors, data on this subject are available from all parts of the oceans, and attempts have been made to correlate water temperature, and its changes, with most other elements and factors in the sea; indeed, direct relations have been found.

Sea temperature is directly determined by heat exchange between sea and atmosphere, which in turn is determined by meteorological factors; in addition some part of the heat 'picture' is affected by heat transport by advection.

Elements and factors in the sea other than those mentioned (e.g., mixing processes and standing crop of plankton) are usually closely related to the major factors referred to above and can therefore be deduced from them.

## EARLIER WORK ON FORECASTING IN THE SEA

The prediction of tides in coastal areas has been practised since ancient times. During and shortly after World War II, methods of wave forecasting were developed and put into routine use by some countries. Ice forecasts for fisheries and navigation have been made by northern countries for many decennia. Prediction of other factors has been very sporadic and almost no attempt has been made to establish a complete hydropsis.

Big temperature variations from year to year in the surface water of the Norwegian Sea, and their causes, were analysed by the Norwegian oceanographers Helland-Hansen and Nansen. They concluded that the major causes of these variations are to be found in variations in solar radiation, that the changes in air temperature precede changes of water surface temperature, and that the winds are the principal cause of the temperature variations of the

surface layers. Wind action also causes the surface waters to pile up and there is, therefore, a positive correlation between water level and temperature along the European coast.

It has long been recognized in Japan and elsewhere that temperature conditions in the surrounding seas govern the air temperature over the land and influence the annual agricultural field crops. Suda, the Japanese hydrographer, found that during a 'cool summer' in Japan, the sea surface temperatures of the whole North Pacific was low, cooling in the region of low temperature having taken place in the preceding cold winter. In a good harvest year, the contrary occurred. As a consequence, it was suggested that the movement and distribution of *kisomizu* (water of low temperature) be studied and the results used in making forecasts of temperatures in summer.

Attempts to forecast water temperatures may be grouped in two categories: prediction by correlation and long-term trends, and short-term forecasting by considering the heat budget of the sea.

In Japan, Watanabe and Hirano tried the 'long-term trends' method, computing a correlation between the resemblance and the temperature anomalies for four different areas west of central and southern Japan. In Canada, McLellan and Lauzier considered the cyclic nature of the variations of temperature in past years around eastern Canada and concluded that long-term trends can be forecast with some confidence. They also considered possible changes in the fisheries of some Canadian waters in the event of predicted decreasing water temperature.

Millar treated temperature changes in the Great Lakes of North America statistically, and showed the possibilities and limitations of statistical temperature forecasts for eight days, based on one past temperature observation and the normal annual curve. He concluded that predictions could be improved by using more past observations and an elaborate regression formula.

It can be concluded from the above-mentioned attempts that predictions from annual curves are unsatisfactory and do not give desired accuracy because, as was pointed out by Helland-Hansen and Nansen, considerable variations which are not shown by the curves and which must be known occur from year to year.

The heat budget method has been used by several workers in different parts of the world with satisfactory results for prediction of seasonal averages and, in a few instances, short-term conditions also. Nearly identical formulae have been used by these workers.

## HOW TO FORECAST CONDITIONS IN THE SEA

Although a considerable amount of oceanographic information is available, relatively little of it is directly useful for hydropsis, because the data have been collected and worked upon with other aims in mind. Therefore such forecasting techniques as can now be developed may be crude from a scientific point of

view. The forecasters' skill in predicting trends becomes one of the important tools in hydropsis.

In hydropsis, the main emphasis is on the prediction of changes of surface waters, as caused by the day-to-day changes in meteorological conditions. It is often difficult to assess separately the intensity of the influence exerted by the factors that tend to change the temperature of the water or influence currents, because controlled experiments at sea are difficult to conduct and the collection of data at sea is expensive.

In hydropsis emphasis will be placed on the construction of empirical formulae, which, recognizing physical cause-effect principles, will permit practical predictions. The elements and factors represented in these formulae are based on those measured in routine meteorological and oceanographic observations, or are easily derived from such routine measurements.

Prediction of waves is a relatively easy task. The main variable factors are the speed and duration of wind, which can be estimated from daily or five-day synoptic weather charts. The average length of fetch is taken from charts appropriate to the locality and direction of wind. Trends corresponding to changes in force and direction of the wind must be estimated by the use of simplified empirical relations.

Wind data also may be used for the estimation of wind currents, of which the empirical relations are well established. Some controversy still prevails concerning the deviation of the direction of the current from the direction of the wind. However, this deviation is greatly influenced by local topography and by superimposed permanent currents.

It seems that the best approach to the prediction of tides in off-shore waters would be to predict the times of slack tides, by use of coastal tidal data and co-tidal lines. Direction of the rotation of tidal currents is usually known in most localities. The shape of the tidal ellipse and the maximum strengths of tidal currents must be estimated from direct measurements with proper current crosses under certain ideal condition (e.g., during minimum strength of wind currents) in some localities, or estimated from model studies. The estimation of tidal heights, if necessary, must also be based on measurements with pressure gauges anchored in midwater. We do not know yet to what extent internal tidal waves, which cause fluctuations in the depth of thermocline in all areas, are connected with surface tidal waves. This matter needs urgent investigation by direct observation. The estimation of the amplitude of the tidal fluctuations of thermocline depth also needs further study. According to experience, this amplitude is related to: depth of the thermocline, the sharpness of the decline and stability of the water.

In certain cases the influence of meteorological tides, caused by changes in atmospheric pressure and piling up of waters by wind action, must be added to the effects of astronomical tides, i.e., those due to the influence of the moon. In areas with extremely low tides, such as the Baltic and Mediterranean

seas, it is only the meteorological tides that cause changes in sea level and depth of thermocline. These meteorological tides can be estimated by the use of some empirically established relations.

Prediction of temperature structure is a complicated task, but enough is known for these predictions to be attempted.

In order to undertake temperature forecasts rationally the procedure can be divided into four major stages and a group of auxiliary steps:

1. Computation of the heat exchange between the sea and the atmosphere, using the meteorological elements that affect local changes of water temperature (insolation, back radiation, evaporation, convective heat exchange, etc.).
2. Computation of absorption of radiation at various depths in the sea.
3. Estimation of temperature structure in a given locality as determined by the earlier temperature, factors 1 and 2 above, and turbulent mixing. Average depth of the thermocline will be estimated from wave data. The amplitude of fluctuations and the times of extreme position should also be taken into account when necessary.
4. Addition of the changes of temperature caused by advection to available data on currents.

The auxiliary steps will relate to other factors such as temperature changes in coastal areas caused by run-off, heat from dissipation of wave energy, effects of the variations of sea level, ice cover, and movement of current convergences and divergences which are caused by temperature boundaries.

If necessary the small changes of temperature in deep water (200 to 1,000 metres) can be estimated from seasonal curves. Seasonal and long-term changes on the other hand could be estimated from the long-term changes of meteorological conditions and from the data of a few, properly spaced, oceanographical stations.

The heat exchange between the sea and atmosphere and the heat gains or losses causing temperature changes in a given locality consist of the following components: insolation (short-wave radiation from the sun and sky), geothermal heat from the bottom of the sea, heat from dissipation of wind and tidal energy, heat transferred by fresh water run-off, heat released by chemical processes, heat transfer by condensation of water vapour, effective long-wave back radiation from the sea, the reflectivity (albedo) of the sea surface, convection of sensible heat, heat loss by evaporation, heat transport by precipitation and heat transported in or out of the area by currents.

The geothermal heat from the bottom, the heat from dissipation of wave and tidal energy and the heat from chemical processes are found in most of the ocean to be much smaller than one per cent of the insolation and can therefore be ignored for practical purposes. Heat transport by fresh water can be ignored in off-shore areas. Heat transport by precipitation needs to be taken into account if there is a considerable amount of precipitation and if the

temperature of the precipitation differs considerably from the temperature of the sea surface, or especially if the precipitation is in the form of snow or hail.

The daily insolation is computed by means of an empirical formula, using the noon altitude of the sun, length of the day, and cloudiness (types and arrangements of clouds). If, on the other hand, insolation is measured on ships, or with self-recording and reporting buoys, the formula used allows for intrumental estimation of cloudiness and, in the case of high cloudiness, visibility also.

Reflected radiation is estimated as a fraction of insolation or is directly related to the altitude of the sun. Effective back radiation is estimated by a synthetic formula, using the temperature of the sea surface, relative humidity and cloudiness.

Evaporation is estimated with a modified Dalton's formula, using wind speed and differences between the saturated water-vapour pressure at the temperature of sea surface and the actual water-vapour pressure of the air at the height of ship's bridge (i.e., 8 metres). In the case of negative values this formula gives the amount of condensed water at the sea surface. The actual amounts of evaporation are multiplied by the latent heat of evaporation, giving the heat loss.

The convective transfer of heat to and from the sea surface is computed by means of a formula derived from the evaporation formula, taking into account the amounts of air having possibly been in direct contact with the sea surface.

Additional factors of the heat exchange of ice-covered seas such as conductivity of ice and its reflectivity must be considered. It is also obvious that the conditions of air stability affecting the wind speed close to the surface must be taken into account by estimation of evaporation and transfer of heat by conduction.

Before considering the absorption of the energy in the sea, one must give some thought to the optical properties of the water, which affect this absorption. As actual measurements are often not available a practical alternative is to define some broad water masses on the basis of optical, temperature and salinity characteristics and range of seasonal changes and coastal influence corresponding roughly to the air masses in the atmosphere. Coastal and off-shore waters are easily distinguishable by various main features, thus:

Oceanic waters (and areas): (a) areas and waters outside the continental shelf (depth greater than 200 metres) and/or (b) oceanic waters of normal salinity, not modified by coastal influence (run-off and turbidity).

Coastal waters (and areas): (a) areas and waters on the continental shelf and/or (b) coastal waters of low salinity influenced by run-off; usually with high turbidity.

A further division of oceanic water masses can be made on a geographical

basis taking into account salinity and temperature and their seasonal changes. The values of these properties, given below, are approximate average criteria: polar—waters of low temperature (below 8°C.) and low salinity (below 34‰), relatively small seasonal change in salinity, and temperature; boreal—waters of medium temperature and salinity, relatively large seasonal changes; tropical—waters of high temperature (above 20°C.) and usually high salinity (above 35‰); in the doldrums, however, the surface salinity may be relatively low, owing to precipitation; small seasonal changes.

Various terms have been used to describe mixtures of different water masses. For hydropsis the following terms may be selected: subpolar—mixture of polar and boreal water masses; subtropical—mixture of boreal and tropical water masses; boreal (mixed)—mixture of polar and tropical water masses; slope water—mixture of off-shore and coastal water masses.

Since, before temperature changes can be computed, it is necessary to know how much radiation is absorbed by various layers in the different water masses, the optical properties of the water masses must be classified. These optical properties are an index of the productivity of the waters, and sometimes, of their origin. It should be noted that a very detailed classification is possible only when actual measurements have been made and that the optical properties of water masses can change relatively rapidly to a certain degree (e.g., by plankton bloom, upwhirling or sedimentation of minerogen suspension, etc.) which makes a detailed classification superfluous. However, identification of the following five optical water masses is useful: (a) oceanic, clear—'old' clear oceanic waters in low-productive areas (especially in low latitudes), water colour 0 to 2 by Forel Scale; (b) oceanic, normal—medium-productive oceanic waters in medium and low latitudes, water colour 2 to 5; (c) oceanic, turbid and coastal, clear—high-productive oceanic areas, especially during plankton bloom, tropical coastal waters, especially over deep shelves, water colour 5 to 8; (d) coastal, normal—normal, medium-productive coastal waters and waters over shallow shelves, water colour 8 to 10; (e) coastal, turbid—estuarine and coastal waters during intensive plankton bloom and waters close to the coast where much sediment has been whirled up by wave action, water colour 10.

Knowing now the extinction coefficient of the waters and the heat balance as computed earlier, we can compute the heat loss or gain in different layers. However, the upper layers of the sea are usually well mixed and the main temperature changes occur in this layer. The depth of this layer is determined mainly by two factors: convective stirring when the heat exchange is negative, and wave action. These factors are also used for estimation of the thickness of this layer. In certain cases, mixing by currents may also be of importance.

The horizontal transport of heat by currents is to be estimated from the current data and from the horizontal temperature gradient.

The estimation of the horizontal movement of current boundaries (diver-

gences and convergences) can be carried out at present only by rule-of-thumb methods.

An area in which single calculations for hydroptic forecasts are to be made should not be greater than 5 degrees square because this is the area appropriate to local changes of elements to be considered, and because several heat-exchange computations must be made for larger areas. In forecasting temperature changes in a given locality the effects of heat advection by currents must be considered. Therefore the possible directions of inflow into the selected hydroptic areas must be ascertained and separate heat-exchange computations made for these adjacent areas from which advection is expected.

Although the majority of the formulae have been worked out for 24-hour-period predictions, a longer period of, preferably, one week, will be used in most practical cases, because the sea reacts much more slowly to temperature changes than the air (a rate of change of properties in the air during a day is roughly the same as the rate of change in the surface layers of the ocean in a week).

Hydroptic calculations are usually for a seven-day period, therefore day-to-day sea-surface and air-temperature variations due to advection must be taken into consideration in making an extended (e.g., five-day) weather forecast. General seasonal trends are usually deducible from hydrographic and maritime meteorological atlases and to some extent can be used in place of long-range weather forecasts, for estimation of trends of meteorological elements. As day-to-day meteorological data become available during the hydroptic period, a new calculation for each day can be made to correct the original hydroptic forecast. These corrections are especially necessary when no actual weekly hydrographic-station or sea observations are made in the hydroptic area. Therefore, these 'back corrections' can ensure to a certain degree that, for the start of the next hydroptic period, the starting conditions in the sea are close to real conditions.

An hydropsis can be presented on charts, in codes for easy transmission and in descriptive form in words. It can be formulated to describe and forecast conditions in a limited area of interest, e.g., on a fishing ground. The distribution of elements and factors in a large area can be described and their trends during the coming week can be indicated with the same ease. Hydropsis can be followed with specific statements for shipping and fishing: e.g., prediction of the arrival of fish to spawning ground, depths and areas where certain commercial fish are expected to be found in quantities, etc.

## EXPECTED ACCURACY OF HYDROPTIC FORECASTS

The accuracy of the forecast depends mainly on three factors: the accuracy of the formulae used, the correctness of the identification of factors to be used in these formulae and the availability of values for them, and on the accuracy

of observation of changes in these meteorological factors. In most cases existing formulae and relations or those to be established can be fairly accurate (of the order of $\pm$ 10 per cent). Since values for the meteorological factors (wind direction and speed, humidity, etc.) will be scarce in most sea areas they must in the beginning be represented by monthly averages and a few observations. The number of observation points can be increased by fisheries research vessels and fishing vessels observing and reporting through appropriate telecommunication. Furthermore the development of self-recording and reporting buoys is proceeding rapidly; these might be anchored at key positions, that is, in areas where the changes of meteorological and oceanographical conditions are significant and determine structure and processes in other areas (e.g., current paths and current boundary, etc.).

The third factor, variability of meteorological conditions with time, depends largely on the possibilities of improvement of long-range weather forecasts. These improvements in turn will depend greatly on the possibilities of co-operation between oceanographic and meteorological forecasting.

## THE FUTURE OF OCEANOGRAPHIC FORECASTING

Basic research has given us some understanding of interactions between natural factors and will continue to add to this understanding. When the use of forecasting in the ocean becomes an international reality, more questions will be asked of basic science and its importance will be more appreciated.

At present oceanographic forecasting is practised to only a limited extent by a few maritime nations. In the last few years the need for international collaboration in this field has been recognized and steps have been taken to this end by international organizations, such as the Commission for Maritime Meteorology of the World Meteorological Organization and by the Hydrographical Committee of the International Council for the Exploration of the Sea. It is obvious that progress is bound to be slow in the beginning and that only those aspects of forecasting which are inexpensive and offer great economic gains will be attempted. Furthermore, it is natural that meteorological, oceanographical, fisheries and navigational institutes must co-operate closely in such international schemes and that the oceanographic service must be organized in a form similar to the existing meteorological service. It is assumed that the development of special instruments and analysing apparatus, particularly self-recording and reporting buoys, will greatly hasten progress in this field.

# THE INFLUENCE OF SEA-FLOOR CONTOURS ON STRUCTURAL ENGINEERING IN COASTAL WATERS

*by*

A. G. DE ROUVILLE

*A. G. de Rouville is a retired inspector-general of the Ponts et Chaussées Department of the French Ministry of Public Works; Honorary Director of Lighthouses and Buoys; professor emeritus of the École Nationale des Ponts et Chaussées (where he lectures on marine engineering); and also member and former president of the Académie de Marine.*

When, in July 1959, we were requested by Unesco to write an article dealing with the influence of the sea on society, we suggested that our remarks might be confined to a less ambitious and, if we may say so, more down-to-earth subject. This article then is concerned with man's struggle to defend coastal areas and ports against the destructive violence of the oceans.

For a long time, sea walls and coastal reinforcements were left exposed to the ravages of the waves and few attempts, apart from appeals to earlier experience, were made to calculate the exact strength required of such structures. Admittedly, with the meagre knowledge of hydraulic science possessed in the past, any such attempts would have been more or less useless.

It used to be thought good enough to copy reinforcements of this sort which had stood the strain in certain circumstances, or to apply the principles used for such reinforcements to the construction of others (even in our day, of course it would be wrong to reject such empirical methods out of hand when dealing with a field such as this in which the instinct and judgement of the engineer are still of importance). The result was that there were a number of accidents, and though the exact cause could not always be discovered, something was learned from the experience and each time work was begun again on a firmer basis.

It must be admitted that we did no better with our Lighthouse and Beacon Service in France; it is true that there have never been any catastrophes in connexion with large lighthouses, because their strength was calculated so as to be more than adequate for their purpose—to support heavy machinery which had to be kept constantly under inspection—but the same cannot be said of smaller beacons which were built with greater regard for economy; set on the edge of rocky headlands, and exposed to the full force of the waves, such structures were sometimes not really strongly built until there had been three or four disasters and they had been strengthened on several occasions.

A more scientific attitude to such questions is of only very recent date. It may in fact be said that the publication of any appreciable number of books on swell and its dynamic action only started just before the second world war, although there were of course certain forerunners ahead of their time, like the surge, so often unobserved, that precedes a violent storm.

However, a list of such publications would, no doubt, take up more space than the whole of this article, and we may be forgiven by both their authors and our readers if we only refer to them briefly and quote short extracts.

One or two articles were published on the mathematical values of the waves and the effect of swell on coasts and ports, and this led to the publication of a great many others, enlarging upon them. Some people were sceptical about these works, as always happens when any fresh venture casts doubt on accepted ideas—or even a complete lack of ideas—or on the conclusions of those who rely solely on an instinctive appreciation of a subject.

This mathematical approach probably began with the theories on the reflection of simple undulation when it met vertical walls, which stood the strain better (that is, with comparatively slight deterioration for a smaller volume and less financial outlay) in very deep water. In this respect mention should be made of the succession of theories on completely or partially broken water put forward by Bénézit, Sainflou, Lira, Coen Cagli and Iribarren Cavanilles—all notable twentieth-century engineers.

It was gradually admitted that vertical sea-walls could be calculated and that a polygon of forces could be established for them; but empiricism still reigned when it was a question of sloping structures against which the waves broke and expended their force, under conditions that could not easily be calculated.

More recently, at the Navigation Congress in Rome (1953), discreet efforts were made, notably by Messrs. Iribarren Cavanilles and Larras, to introduce a certain amount of mathematical calculation into the construction of the latter type of reinforcement, by expressing as a formula the state of equilibrium of a block which is subjected to the force exerted by its own weight on the one hand and the force exerted by the sea against its surface on the other. The empiricists were somewhat disconcerted by this slight innovation.

On this occasion, attention was drawn to the influence of the angle of inclination and the density of the blocks on the strength of such reinforcements; similarly, the force exerted by the waves depends not only on the amplitude (or the depth of the trough) but also on the length which determines how soon a wave will break after 'feeling the bottom'. This involves a distinction in hydraulic formulae according to whether the case considered is in the open sea or at a depth equal to half the length of the wave.

If we first take the ideal case in which the bathymetric lines (i.e., the lines of equal depth) are parallel to each other right up to the coast, and to the wall which is exposed to the sea, it will be seen that the waves beat against the wall

regularly and at the same time along its whole length. This is a great disadvantage, for the different parts of the wall form, to a certain extent, a single block, and they stand the strain better if they receive the shock one after the other, so that it is slightly staggered.

In such circumstances, the over-all resistance of a sloping sea-wall will be increased if the angle of inclination of the lower parts of the wall is calculated according to the force exerted upon it by the waves and the slope extended below the level where the waves break heavily, and if the facing blocks are properly overlapped and their surface left rough so as to absorb some of the force.

In recent years, one or other of the following devices has been used to secure better overlapping. It has been found that concrete blocks called 'tetrapods', consisting of four broad legs spreading outwards from a common apex, are less likely to separate or become detached from a sloping wall than ordinary blocks, and particularly less than parallelopiped blocks; and in this way it is possible, other things being equal, for the blocks which have to be handled to be fairly light in weight (maximum 50 tons) and for one of the sides of the wall (the lower one) to be slightly reinforced, with a consequent gain in volume.

The gaps in the embankment are bound with a mixture of sand and bitumen, which holds the parts together and keeps the structure firm in spite of settling and rolling movements. The initial cost of construction is considerably higher but there is less subsequent loss of material.

Of course, in the case of a retaining embankment with a vertical facing, the strength is determined mainly by the depth of the wall under water at the lowest point (at least twice the depth of the trough of the largest waves). If the depth is sufficient, there will be a real reflection or formation of clapotis, instead of the waves breaking partially, which occurs in some cases where the sea is of medium roughness or where only the superstructure, to about the level of low tide, is approximately vertical. Another factor to be considered is the prevention of scouring at the base of the breakwater, which is constructed of enrockments; foundations on rock bottom are naturally protected; in other cases, scouring may be prevented by layers of brushwood or rubble.

The procedure recommended in the case of sloping sea-walls is to some extent suitable for lengthwise retaining walls, which must be constructed—unfortunately, at considerable cost—on such coastal strips as bathing beaches or built-up sea fronts if the action of the waves is more or less head on, and if there is no appreciable deposit of pulverulent material which would make it possible to protect the off-shore bar by a series of spur dikes and fill them with this material.

The slope of these retaining walls should be dictated by the force exerted upon them by the sea-waters, as in the case of a sloping embankment; inclination should be between three and six (as in the Netherlands) horizontally at the base to one vertically; however, as such protective walls are usually built

with a core of loose material which is liable to be scoured (such as sand from dunes), it would be dangerous to allow the waves to reach it; the facing should therefore be made as watertight as possible, or else it should be superposed on a series of layers of rubble, which should decrease in size as the ground is approached; it is even a useful precaution to insert, where possible, a layer of clay or straw as well as one of quarry chips; a watertight wall, however, must be capable of standing up to the force and erosion of the sea and of the material transported by it (which may be sand, or even shingle).

In constructing walls of this type, it is therefore advantageous to incorporate in concrete blocks rough shingle, a number of spikes formed by basalt pillars (e.g., the basalt obtained from the Eifel plateau, in Germany, for use in the Netherlands), or stakes embedded in the concrete to break the force of the waves.

However, while it is desirable that these facings should be watertight and firm, they should yield to the inevitable movement to be expected in a structure built on or against strata of loose or shifting ground; for this reason large slabs of reinforced concrete are inadvisable; they soon disintegrate because cracks form and they split apart; and they add to the arsenal of destructive material tossed about by the sea. It is preferable to use smaller sections such as naturally formed rubble or concrete parallelepipeds, basalt blocks (Netherlands) or blocks of other solid materials such as ophite (near the Pyrenees), which may if necessary be jointed, not with cement, since the layers of cement would crack and separate irreparably, but rather with bitumen; some firms now understand the process of applying it in the right proportions and while hot.

It is, of course, necessary to see that the bottom of such walls is protected for as long as possible against scouring, while at the same time the low angle of inclination should prevent any lowering of the level or deterioration of the beach which, after all, the wall was designed to protect.

If necessary, the inclination of this revetment may be further reduced at the base by sinking it into the ground on the beach, and the bottom may be covered with a few enrockments, although care should be taken not to use anything which might tend to produce further erosion by reflection on a vertical surface exposed to any shock.

It will, in any case, be advisable not to run the risk of exposing vertical sea-walls. This does not refer to walls in water of reasonable depth (15 to 30 metres), since an exposed surface is essential to their action of reflection, but to those close to much greater depths, as the long heavy waves of the open sea would then break head on against these comparatively thin walls, merely resting on an underwater base.

It will be seen that the engineer must have a considerable knowledge of the steepness and varying levels of the sea floor, for the angle of the declivity away

from the shore determines the force of the sea's impact on protective or retaining walls. The terrific impact of the waves on embankments of this sort is not regarded as such an amazing phenomenon nowadays when it is known—or as sometimes happens, even these days, when it is discovered afterwards—that there is a sharp rise in the level of the sea floor just a short distance out from the harbour which is to be protected.

For a long time it was thought sufficient to take soundings around the proposed site of a sea-wall. From one point of view it was rightly considered an advantage to have deep water nearby, since this means that the largest ships can enter the harbour without any appreciable dredging being necessary, but the engineer who is subsequently entrusted with the maintenance of these embankments may see the situation in a different light.

This will help to explain why other reinforcements which are of lighter construction and are equally exposed to the sea withstand the shock easily under apparently similar conditions; the reason is that a wide platform just under sea level has absorbed some of the force of the waves, diminishing them in both length and height (e.g., as at Ymuiden).

Paradoxically, however, it may increase the height of waves caused by wind and even high tide, so that in certain circumstances the waves which break against the coastal embankments are larger (as, for example, on the shores of the North Sea in February 1953), the effective sheet of water being unduly increased in depth.

When the bathymetric lines clearly run obliquely to the coastline, so that the wave crests also remain oblique to it for a considerable period, and when, consequently, the direction of the waves beating against the coast is at a marked angle to a protective wall constructed along the coast, the problem of withstanding the shock is rather easier to solve, for the very fact that the force exerted is at an angle means that it is reduced, since the different sections of the embankment support each other a little more; besides, any loose material which the sea detaches from the ocean floor may fall on these parts of the embankment as it is deposited on the foreshore, and this material may be collected by a series of spur dikes, thus forming a protective coating.

The same favourable conditions do not apply when a wall constructed to protect a harbour is at an angle to the waves (which incidentally is not the most economical way to build, since a greater length is required to protect the same area); this is because the water surges at the bottom of the slope of the breakwater and hinders the formation of a deposit of sand there. Yet the impact of the sea is somewhat less if it strikes the breakwater at an angle. Even an oblique structure should, however, be built to withstand a frontal onslaught, which may be at the sea's full strength or not, depending on the direction and fetch of the prevailing winds.

The engineer's only help in forecasting the probability of a frontal or oblique

onslaught by the sea and the maximum force that will be reached is to study the contour lines of the ocean floor and charts showing the directions of wind and swell.

These facts have been known for a long time, but the fact that the shock will be greater or less according to the plan of the bathymetric lines is a matter of comparatively recent knowledge.

To take a minor aspect of the question, we may refer to a relatively unimportant personal experience on the beach at Berck (Pas-de-Calais), where we were trying to discover the way in which the extremely varied ridges in this area are formed: at high tide, the waves beat at right angles against the coast, except over a short stretch where they came in obliquely with more force; the explanation became obvious at low tide, when the nearest sandbanks were scarcely uncovered and a gap could be seen between them; the waves came in at an angle through this deeper passage; they were higher because they were deflected by the adjacent banks, and reached the coast at full force, without any marked change of direction.

Since then, a great deal of survey work has been carried out by the most efficient methods and with the help of all the theoretical and mathematical knowledge which has a bearing on the problem. When the lines indicating the same depth of the sea floor near the coast are neither regularly spaced nor more or less parallel, a section of the wave crest is slowed down in shoal water; the crest line either bulges or recedes and is slightly deflected from the line of the waves in the deeper parts; it may be said that the rate at which the waves 'feel the bottom' depends on the depth of the sea floor. Generally, the wave tends to align itself with the bathymetric lines towards which it was directed independently by the wind before any influence of the bottom contours made itself felt.

So then one can draw up a 'plan of waves', to use the term coined by Mr. Ramòn Iribarren Cavanilles, the well-known Spanish engineer, who has also described how such a plan can be constructed.

On this plan several trajectories can be drawn, either curved or straight, which are always perpendicular at each of their points to the wave crests, the outline of which changes with each successive deflection.

As a general approximation it may be said that there is very little reflection of the waves from the sea floor where the latter is in its natural state and is on the whole at a gentle slope, and that no energy can cut across these perpendiculars.

The picture therefore becomes very clear both to the eye and to the mind, for the perpendiculars (orthogonals) are actually seen to be closer together towards the submarine capes or shelves and more widely spaced in the submarine bays and valleys (see the figures on pages 138 and 139).

This also gives an indication of the energy transmitted to the earth by the sea. It is possible to find the formula for this energy, which depends largely

on refraction; and its distribution corresponds quite closely to the idea formed by any ordinary observer of the sea or the most primitive navigator. For the movement of the sea is at its most violent and sometimes at its most confused at the capes, because of the clash of two lines of converging energy; and the land surface is also most rapidly eroded at the capes, the projecting points being left only because the rocks which form them are hard or because additional material has been deposited there.

Comparative calm where ships may lie at anchor is to be found in bays where the orthogonal lines are wide apart, and here, too, the structural works are subjected to less severe pounding from the waves and to less exposure, at least on some types of bottom.

When a number of these orthogonals run through a breakwater exposed to the open ocean or converge upon a coastal embankment, the onslaught of the sea will be most vigorous.

More plans of the waves should be made, showing the most common directions of the waves or periods of swell, for thus a much wider variety of wave patterns could be observed.

But as the phenomenon of refraction tends to bring these wave crests into closer alignment with the contour lines, which are more or less fixed, the waves originating from different quarters tend to form the 'long crests' which cross each other as they approach the shore.[1]

The average energy transmitted through the unit of length of a crest during any period is proportionate to the square of the amplitude of the swell at that point and also to the rate of movement of the group of waves at the same point, which is in turn a dependent variable of the relation between the depth and the wave-length of the swell.

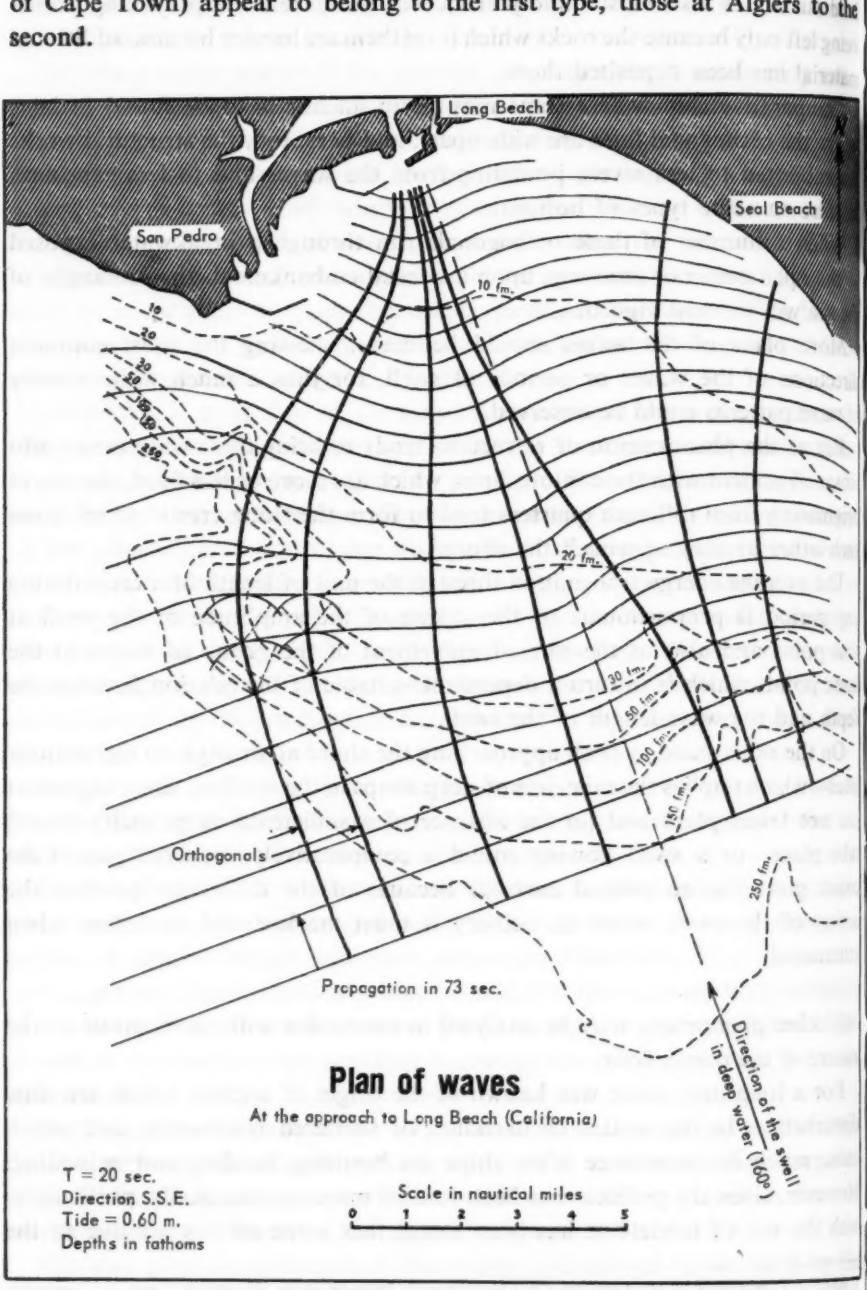
On the other hand, a swell approaching the shore at an angle to the contour lines—which implies the existence of steep drops in the sea floor since alignment has not taken place and (in the absence of a sufficiently large shelf) cannot take place—or a swell flowing round a comparatively sheltered part of the coast, gives rise to coastal currents because of the difference between the action of the swell where its activity is most marked and its action when attenuated.

Still other phenomena may be analysed in connexion with the contour or the nature of the ocean floor.

For a long time, little was known of the origin of seiches, which are slow disturbances in the waters of harbours or sheltered roadsteads, and which cause much inconvenience when ships are berthing, loading and unloading. However, since the problem has been studied more systematically, particularly with the use of models, it has been found that some seiches are due to the

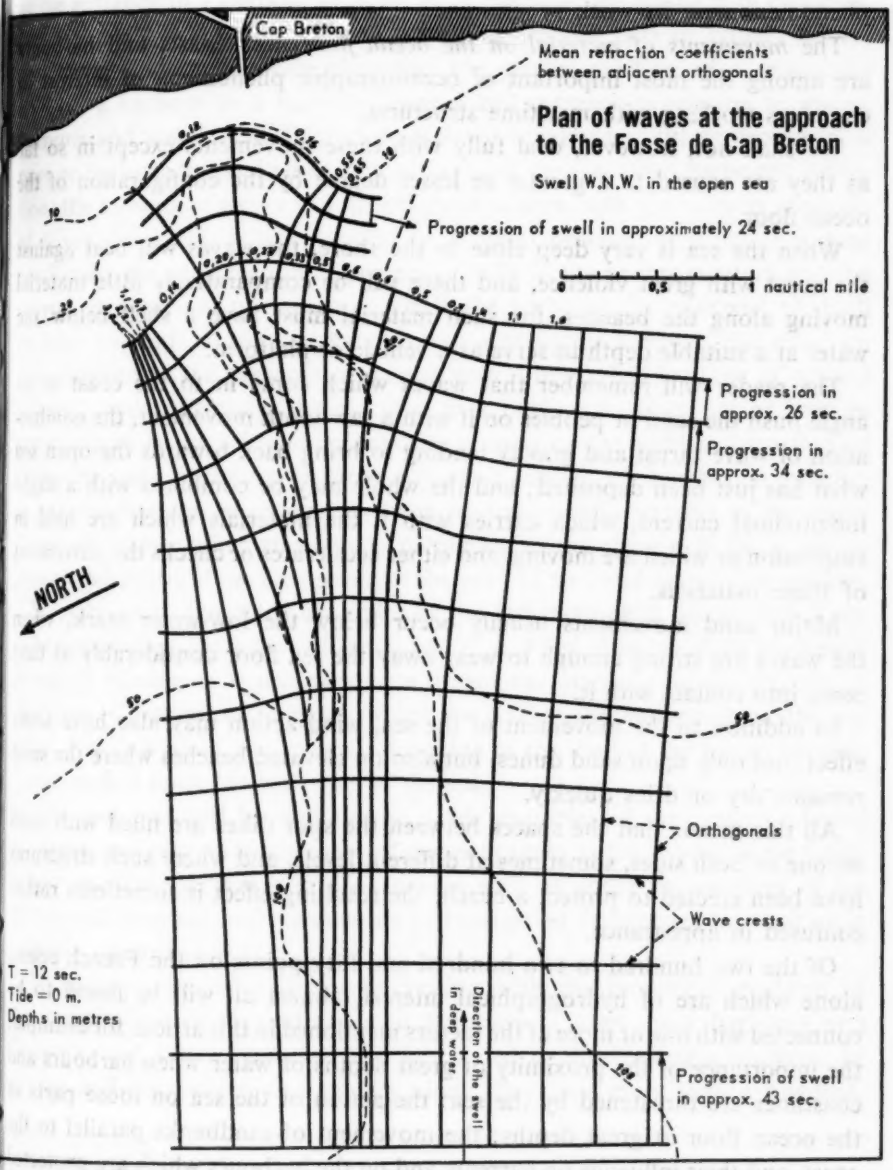
1. Based on a description by Mr. Lacombe, Chief Hydrographic Engineer, in the *Annuaire du Bureau des Longitudes*, 1959, p. 526.

disturbing action of swell partially reflected from the opposite shores of a bay or harbour, although other types of seiche (which we cannot pause here to discuss) are the result of the periodic breaking of a series of waves on adjacent beaches. The seiches at Tamatave (Madagascar) and Table Bay (the harbour of Cape Town) appear to belong to the first type, those at Algiers to the second.




From the course of lectures by Mr. H. Lacombe, Chief Hydrographic Engineer

However, the various waves which make up a swell must always be analysed, because the meeting of these waves may cause the formation of 'series' of waves at more or less regular intervals; and, if these waves or series of waves correspond either directly or by multiples to the natural period of fluctuation of an enclosed mass of water, they may bring about a disturbance in the form of a seiche.


Cap Breton
Mean refraction coefficients between adjacent orthogonals
Plan of waves at the approach to the Fosse de Cap Breton
Swell W.N.W. in the open sea
Progression of swell in approximately 24 sec.
0 0,5 1 nautical mile
Progression in approx. 26 sec.
Progression in approx. 34 sec.
NORTH
Orthogonals
Wave crests
T = 12 sec.
Tide = 0 m.
Depths in metres
Direction of the swell in deep water
Progression of swell in approx. 43 sec.

From the course of lectures by Mr. H. Lacombe, Chief Hydrographic Engineer

Generally speaking, insufficient study has as yet been made of the problems connected with this phenomenon, which are encountered in harbours throughout the world, for it to be possible to make a conclusive statement as to the relations between cause and effect which we have outlined above and which are very closely concerned with our subject.

The International Committee on Wave Action of the Permanent International Association of Navigation Congresses has placed the study of this phenomenon on its work programme.

The *movements of material on the ocean floor* near coasts and harbours are among the most important of oceanographic phenomena of interest to engineers working with maritime structures.

We shall not, however, deal fully with these movements except in so far as they are caused to a greater or lesser degree by the configuration of the ocean floor.

When the sea is very deep close to the shore, the waves will beat against the coast with great violence, and there will be comparatively little material moving along the beaches, for such material must have a shelf below the water at a suitable depth to serve as a vehicle or platform.

The reader will remember that waves which come in to the coast at an angle push the sand or pebbles on it with a saw-tooth movement, the combination of wave thrust and gravity tending to bring back towards the open sea what has just been deposited; and the whole may be combined with a slight longitudinal current, which carries with it the materials which are held in suspension or which are moving, and either accelerates or checks the movement of these materials.

Major sand movements usually occur below the low-water mark, when the waves are strong enough to wear away the sea floor considerably as they come into contact with it.

In addition to the movement of the sea, wind action may also have some effect, not only upon sand dunes, but also on elevated beaches where the sand remains dry or dries quickly.

All this means that the spaces between the spur dikes are filled with sand on one or both sides, sometimes at different levels, and where such structures have been erected to protect a beach, the resulting effect is sometimes rather confused in appearance.

Of the two hundred to two hundred and fifty points on the French coasts alone which are of hydrographical interest, almost all will be found to be connected with one or more of the factors mentioned in this article, for example: the importance of the proximity of great depths of water when harbours and coastlines are threatened by the sea; the action of the sea on loose parts of the ocean floor at great depths; the movement of sandbanks parallel to the coast, and their influence on currents and on the harbours which are protected by them; breaches in these lines of sandbanks; local conditions influencing

currents or counter currents in bays; the combined action of the current and the waves on the maintenance of a harbour channel; the conditions under which the waves will reach the end of gulfs; the movements of the waves around headlands; the effect of a headland on currents; the erosion (normal) and the building up (more exceptional) of capes; the importance of a rock or an isolated sandbank at the approach to a harbour or channel, or its power to diminish the effect of coastal erosion; the effect of a solid jetty on conditions at the entrance to a harbour or in an outer harbour; the problem of estuaries, and especially deltas; the effect of waves on harbour bars or estuary banks, and the formation of such obstacles; the proper position of a protecting wall for a harbour or a harbour channel and entrance in relation to waves, currents and winds; the effect of an isolated breakwater; the protection of a port or harbour by sandbanks; the entrance of the swell into harbours; reflection; the meeting of waves and the effects of seiches, with the various methods of diminishing their effects; natural or artificial beaches; adjacent or distant headlands; the construction of protective walls in the proper position and the correct arrangement of structures within the harbour; the transport of small or large amounts of sand or pebbles into a protected harbour; the effect on this situation of the presence of a river with a heavy bed-load, or of coastal currents, and conversely, the use of a river outflow to clean out or keep in order the outlet of a harbour; deposits of mud or the sudden formation of sludge in some harbours or large estuaries; erosion of beaches in relation to the construction of excessively steep protective walls parallel to the coast. These and many other phenomena pertaining to the erosion of the coastline give an indication of the interaction of the work of man and the work of nature.

In addition to the many examples of the last-mentioned danger which are to be found along the coast of France, Mr. F. A. Allen, director of the Hydraulic Research Station at Wallingford, has drawn our attention to an example at Wallasey (Cheshire) in England, where the wall of the boulevard on the sea front, King's Parade, has caused a lowering of the level of the beach, because it encroached upon the waterline of the sea.

At this point, it will be well to cite a few examples of the 'cases' referred to above, and also to thank those of our colleagues at the International Committee on Wave Action who are working with us under the auspices of the Permanent International Association of Navigation Congresses for their most valuable contributions.[1]

There is an extensive literature dealing with the important problem of the preservation of the entrances to harbours or even outer harbours and channels, and many examples may be quoted to illustrate this problem. In France and the French Community alone, there are more than a hundred.

1. Readers should note that papers prepared by the committee are published at regular intervals in the half-yearly *Bulletin* of the association, obtainable from 60, rue Juste Lipse, Brussels.

Our attention was recently called to an example which shows how carefully the movements of loose material on the ocean floor near a harbour must be watched: the situation of *Dunkirk* in connexion with deposits is neither improving nor deteriorating, although it is fairly well protected against the north and west winds by six lines of parallel sandbanks intersected by channels; the east or north-east winds blow along its roadstead more, thus creating in the outer harbour, which is partly open, a disturbance that helps to keep the sludge which has been raised in suspension. The tidal currents alternate naturally in this roadstead, which goes out as far as the two furthest channels. If any change were to occur in the openings between the lines of sandbanks, it might bring about disturbances in the direction of the currents and cause deposits on the coast, which would make a considerable difference to the approach to the harbour for which the present protective walls were constructed. Fortunately, the Ridens sand ridges in the North Sea are firmer than their formation and their origin might lead one to think.

*Port-Maria de Quiberon*, on the southern coast of the peninsula of the same name (Morbihan, France), is a small but busy local fishing centre; it used to be very rough, and the entrance to the harbour was at times almost innavigable, especially at certain positions of the tide.

It had two channels—a circumstance which sometimes helps to reduce a rough sea. In this case however, after very careful experiments had been carried out on a model, it was at once seen to be necessary to close one of the channels—the narrower one, which is known as the southern channel—as the first step towards improving the situation.

The various disturbances with which this harbour is afflicted are due not only to the fairly rough seas from the west, the force of which is not diminished to any extent by the south-west tip of the peninsula, but also to the fact that the main dike, which is between the two channels, was constructed, with an eye to economy, on a suitably sited underwater shelf. The wave crests at first come in, one after the other, at right angles to this wall, but they are deflected, and follow the contours of the shelf almost exactly; after flowing round it and the end of the dike, they turn round inside the wall and again become almost at right angles to it. They then clash with the waves which have come in through the southern channel. The two wave systems meet and in some places are superimposed the one on the other, which causes broken water, whilst in other places, the crests that are left go dashing against the sides of the harbour, the various other sea-walls and the rocky coast; and this, together with the fact that there is a tendency for a sandbank to accumulate in the centre and encourage the formation of breakers, makes the harbour difficult to enter and unsuitable for anchorage.

On the other hand, the perpendiculars to the wave crests would show that there is a considerable force concentrated on a large part of the dike in the open sea, and this explains why it is repeatedly damaged.

Other remedial measures besides closing the southern channel have been advocated, such as extending the dike in the open sea to form something like an elbow, or constructing a new, rather long breakwater to the east. This, however, is outside our purpose, which is mainly to show the effect of contour shapes at the approach to a harbour and the importance of the observation of models in gaining a clear idea of the interaction of waves.

*The Fosse de Cap Breton:* this depression, which is well known in the literature of hydrography is nine miles to the north of the mouth of the Adour on the southern Atlantic coast of France. Its outstanding feature is that the contour lines of the ocean floor run in towards the coast, from the 1,000-metre line to the 50-metre line, which lies about three miles out of its normal position, so that at a distance of 600 metres from the coast it forms an underwater canyon about nine hundred metres wide.

Then the perpendiculars to the line of the swell swing away on each side of the axis of the depression, leaving an extraordinarily calm area in the midst of the surge that is a distinguishing feature of the whole of this coast; at the same time each of the two groups of orthogonals converges, especially that to the north where the coast they reach is nothing but sand dunes, and was until recently uninhabited.

The French Mediterranean coast has some remarkable features which are sometimes totally different on either side of the meridian of Toulon.

To the east, as far as Port-Vendres, Professor Bourcart has recorded the outlines of a fairly large number (17, if we are not mistaken) of very deep, narrow canyons, which would make the waves beat at their full length against the coasts and the protective walls, causing great damage to the latter, but for the fact that these submarine valleys stop at about the 100-metre contour line.

There may, however, be similar situations which are more immediately dangerous in other parts of the world.

In the *Baie des Anges* at Nice, investigations carried out to ensure the safety of the Promenade des Anglais or the outfall of the sewers have shown that some parts of the basin were more subject to the action of the waves than others; in the absence of direct observation, this could have been explained by an examination of the pattern of the bathymetric lines which, in the direction of Le Carras, show numerous projections and indentations.

The wharf at *Port-Bouet* has now been abandoned. It is just to the east of the celebrated Trou sans fond and the new port of Abidjan, and the sea approaching it was reputed to be somewhat rougher than at these places or on the coast of the Gulf of Guinea which stretches away to the east, where there are other wharfs. This phenomenon can be explained by the fact that the shape of the contour lines, which in the north-east follow the Trou, must cause the waves, which are larger and closer to the perpendicular to the coast, to beat against this ancient structure.

A knowledge of this configuration of the ocean floor and its consequences might have led to a decision to build the wharf further back, towards the east, if other considerations had not had to be taken into account.

Other examples may be cited, in France or in North Africa, which illustrate the effect of the configuration of the ocean floor on the coast or the entrance to a harbour. Among such examples are: *Grandcamp* (Calvados, Baie des Veys), which is protected by a steep breakwater; the *Ile de Groix*, which lies across the entrance to Lorient and prevents the formation of a sand-bar; *Sfax* (Tunisia), which lies open to the sea, and which is guarded by the large, grass-covered Kerkennah Islands; *Porto-Vecchio* (Corsica), where the gulf is more protected because of its constricted, twisted form than similar gulfs at Ajaccio, Valinco or St. Florent; *Port-Vendres*, *Calvi* (Corsica) and *St. Jean de Luz*, where the great depth of the sea and the deeply submerged sand-banks, are not sufficient to stop the sea from beating against the protective structures on the coast; *Djidjelli* (Algeria) and *Mazagan* (Morocco) where the presence of a breakwater with two arms, forming a right angle, and the fact that the shallows fan out off the coast, is enough to reduce the force of the breakers or to turn them in another direction.

Our attention has been drawn to the fact that, at Havana, the bay and the port, which are separated from the open sea by a narrow channel with a number of beaches along it, used to be comparatively calm, in spite of the winds which blow from the north-west to the north-east. It was decided, however, to replace these beaches, which obviously served as a sort of series of breakwaters, by a waterfront boulevard with a single protective wall. This meant that instead of the beaches, which absorbed the shock, there was a surface which reflected the impact of the waves; for the last thirty years, this surface has unfailingly perpetuated the rough conditions caused mainly by the strong north-west winds. The result is that anchoring and harbour work are more complicated, and the level of the beach, as might have been expected, has sunk.

At *Eyemouth*, in Scotland, the presence of shallows on the ocean side of the breakwater reduces the height of the waves coming in from the open sea from 20 to 14 feet as they break.[1]

A Portuguese study by Messrs. Fernando Vasco Costa and José Fuiza Perestrello which appeared in the review *Tecnica* for June 1958 (page 643) suggests that on the sea floor—for example, in front of the entrance to a harbour requiring protection against the action of excessively strong waves—a wall should be constructed under the sea, but of very considerable height, or, on the other hand, that a hole should be made by dredging, which would undermine the waves or reduce their amplitude or, by deflection and by refraction, would direct them away from shipping approaches.

1. See W. J. Reid, ' Eyemouth Harbour—a tidal model investigation ', in *Bulletin* No. 48 of the Permanent International Association of Navigation Congresses. Reference supplied by F. A. Allen, director of the Hydraulic Research Station, Wallingford, Berks.

This ingenious idea presupposes, first, that there is an over-abundance of deep water outside an entrance, which is not always the case, secondly, that an underwater structure leaving a draught sufficient for ships which might touch the bottom in rough seas (for example, 12 to 14 metres in the case of a large port) would have an appreciable effect on the amplitude of the rhythmic wave movement; and, lastly, that conditions would be such as to allow for construction at reasonable cost.

From the studies made by Mr. Iribarren Cavanilles (Spain), we know that he has achieved, with quite reasonable outlay, excellent results in diminishing disturbance, and particularly periodic undertow, in some of the small ports in *Guipuzcoa*, by dredging out certain areas, thus altering the period of oscillation in each.

The importance of an idea of this sort should therefore not be underestimated.

At the same time, a method that is successful for a shallow port may not yield good results in passages used by large ships, especially when it is a question of dredging out the sea floor, and not one of building a wall.

Although it is true that deep water effectively transmits the longer waves, it would seem that most of the energy of such waves is localized near the surface. If the waves are undermined, to say 10 metres down in depths of 20 metres, it is possible that a substantial proportion of the force of the waves may still remain above the structure—at least if we may judge by two empirical cases (supplied by Mr. Miche of the Laboratoire Dauphinois d'Hydraulique) which would be of great interest if confirmed by experiments on a model and by theoretical calculation.

At *Mers El Kebir* (near Oran), the original idea was, for reasons of economy, to construct one of the protective walls (the one on the east) under the sea. However, as the artificial wall was gradually built up from the base on the model, it became regrettably apparent that a reduction of two-thirds of the depth (20 metres in 30 metres) gave no appreciable attenuation of the prevailing conditions; a reduction of five-sixths was still not enough, and a reduction of fourteen-fifteenths was necessary to obtain the desired result, which made the scheme pointless.

Actually, the width of the obstacle would probably be quite as important as its height in attenuating the force of the waves; an artificial submarine wall of considerable extent in all three dimensions would therefore have to be constructed—which would hardly be an economic proposition. This theory of the equal importance of width and height is supported by the fact that a line of off-shore sandbanks (even if they are well under the water) and even more a series of almost continuously submerged lines of sandbanks (e.g., six at Dunkirk), can be of considerable value.

A study has been made of a model of a wall, off the Promenade des Anglais (at *Nice*), to be built under the water so that the people on the promenade

cannot see it and extending out to sea to a distance of a score of metres or more. Observation has shown that a wall of this type is an advantage in that it reduces the amount of spray and even pebbles flung up on to the promenade, and slightly increases the size of the very narrow beach available for sun-bathing. However, in this case, if desired results were to be obtained, it was clear, that, where the sea was about five metres deep, the depth of water left above the wall should not be more than one or one and a half metres.

The difficulties encountered by the Belgian engineers at the sandy harbour of *Zeebrugge* are mainly due to the presence of a depression (Appelzak) which corresponds to what was once an arm of the Escaut (the Zwyd). It was thought that this depression would serve for many years as a trap for the large amounts of sand conveyed down the coast by the western tidal current which is much stronger than the ebb-tide close to the shore. For some considerable time, however, it was not possible to keep a watch on the changes in this depression, and from the beginning of the twentieth century onwards it gradually filled up; from the thickening of the arm of land which separates the depression from the harbour, it has been calculated that it has moved back 1,400 metres in 16 years at the —6.00 contour line.

The North Sea beats hard against the island of *Sylt*, the northernmost island in the German Frisian Archipelago—both against the centre, which is occupied by Westerland, the capital of the island, and against the narrow arms which extend to north and south. The sea front of Westerland is in a particularly dangerous position, because the sand appears to be moving in two different directions, forming the elongated arms referred to above, whilst there is no sand left to cover the central protective wall which serves as a promenade. The contour of the bathymetric lines, which, in front of the town, form a wide curve around it with the centre far inside, must help to direct the waves particularly towards this point, whether they come slightly more to the north or to the south of due west.

At *Port de San-Pedro* (to the south of Los Angeles) and Long Beach[1] can be seen the classical American example of the concentration of the force of the waves resulting from the particular contours of the ocean floor when the waves approach from certain directions.

Particular attention has been given to this case because, in 1930, severe damage was caused to a jetty built of rough stones without a cemented superstructure.

The 200, 150 and 50 fathom lines form a bulge thrusting forward five miles (on a 10-mile base) south of Long Beach, which is sufficient to account for the fact that the waves are concentrated on the jetty, and fan out to the west

1. See the *Bulletin* of the Beach Erosion Board, January 1950.

(towards one of the entrances to the harbour) and to the east. The effect is especially noticeable when the waves are coming from the south and from the south-south-east; it is less noticeable when the waves come from the south-south-west and from the south-west, firstly because two islands between twenty and forty miles away and about fifteen miles long, at an angle of 190° to the harbour, shelter it against a swell coming from certain directions, and secondly, because the adverse effect of the waves which come from a more westerly quarter and are broken up by the above-mentioned bulge is felt only along a stretch of coast further to the south than Long Beach (Seal Beach).

Thus the range of a long-period swell (20 seconds) which is over 600 metres in length, caused by a depression in the South Pacific, with undulations of only 70 metres in the open sea, and almost imperceptible since its surface inclination is only 1/900, is multiplied by 7 as a result of the decrease in depth (by 2 approx.) and refraction (by 3.5 approx.). It is not surprising that the jetty which is subjected to this battering should suffer, whilst the force of the waves breaking on neighbouring beaches is not exceptional.[1]

Such contrasting phenomena are an effective answer to those who see no particular necessity to carry out preliminary studies of the configuration of the ocean floor.

There is another concentration of waves at the mouth of the *Hudson River*, at the extreme north of Long Branch, which forms the edge of the right bank; it is due mainly to the canyon of the Hudson, which lies in a north-south direction towards the tip of the land, and then south-south-east further out, to sea. When the waves reach this depression, their direction changes a little, and they tend to converge, so that the formation of two crests brings about a further concentration of destructive force on the tip of Long Branch.

The pier at *Segundo*, which is used by the New Standard Oil Company in *California*, is opposite the steep edge of a plateau 12 fathoms deep; the long waves build up on this edge, and hurl their full strength on the structure, which is exposed to breakers with a trough 20 feet deep, whereas on either side the waves are only 6 feet high.[2]

These are but a few examples; and many more could be quoted from the knowledge we already have. A large number of them would also show what protracted investigations should be made before a new harbour is constructed, if there is to be any certainty about its future and the best way of maintaining it in good condition; for the phenomena involved change in cycles, not of one year, but of 10, 20 or more years.

Now, while political and administrative procedures are sometimes extremely long drawn out, we cannot expect that even they should be delayed until such lengthy hydrographic observations have been completed. It is thus tempting

1. See Lacombe, *Bulletin* of the COEC (Comité Océanographique d'Études des Côtes), May 1950, p. 185.
2. See K. D. Peel, 'Location of Harbours', First Coastal Engineering Conference, 1950. Reference supplied by Mr. F. A. Allan, director of the Hydraulic Research Station, Wallingford, Berks.

to force a conclusion from the first stages of the observations, at the risk of committing errors and encountering unforeseen developments later on.

Fortunately, for some years now, hydraulics laboratories and scale models have been available to help us, in addition to the experience of hydraulic engineers. Thus, the rhythm pattern of tides and swells can be accelerated artificially, so that we can reproduce in a few hours a process which actually takes several years. It is even possible to reconstruct the history of an estuary like the Seine (this has been done at Grenoble), which gives us reason to believe that natural phenomena will continue to behave in a certain way, and that man can devise measures against them.

The investigations made are intricate and call for equipment for measuring and generating swell and tide conditions that are both complicated and expensive; and the collaboration of many scientists in the various branches of physics is essential. It is therefore not advisable to improvise these requirements in new countries, but rather to take advantage of the help that can be offered by the more developed countries. As a rule, the latter are willing to carry out observations on the spot and to use their own hydraulics laboratories to direct these studies which, without such specialized advice, would be useless.

This is one aspect of the international assistance recommended and organized by Unesco. Such co-operation could be made more effective yet and could be undertaken at a higher level.

We have seen what almost irremediable mistakes may be made in designing a new harbour or remodelling an existing one, if the principles of oecanography are not kept in mind—because of the destructive onslaught of the swell, which may be concentrated on one particular section of the dike, or because of the injudicious removal of natural breakwaters, or the reflection of the waves against new or altered structures, or because of a number of other secondary factors mentioned in the early pages of this article.

This sort of carelessness is less forgivable these days, when oceanography has become a science, with greater facilities for investigation.

It would seem, however, that, although in some cases there is still not enough awarences of the position, a good deal of thought is being given to these questions in the older countries which have long had proper marine training, well-indexed documentation and wide experience. This experience might, on the recommendation of an international organization for example, be made available to the 'newer' countries, few of which yet have sheltered harbours.

In any case, there is one condition which must first be fulfilled. Before good ports are designed one must be a convinced that they are worth constructing. In the newer countries, where preference has been given to roads or railways, because they are more spectacular, more quickly built, etc., port construction has often suffered. For too long was it thought sufficient to carry out shipping

operations on the open coast with resultant losses of merchandise, expensive delays, discouragement to travellers and general detriment to the country's prestige; insurance, expensive as it was, did not cover all the losses, and the only possible profit went to the transhipment and lighterage agents.

The most cursory economic study will make it clear that, even if the goods handled amount to far less than 100,000 tons per year, it is still worth while to construct a simple jetty in a sheltered bay instead of unloading on the coast. More expensive protective structures are, of course, only advisable where a greater volume of trade is handled.

International assistance may be of value in this respect, in view of the fact that the sums involved are beyond the resources of countries still in process of development.

Yet, although the idea of a more or less highly developed harbour is now impressed on the minds of technical and financial advisers in countries which do not yet possess such facilities, and although the requirements for efficient port construction can be fairly scientifically deduced from the information supplied by experts and from such practical surveys as they recommend, the same is not yet true of the protection of the narrow frontier that separates the sea, which is the proper field of oceanography, from the land on which the rapidly increasing multitudes of humanity live and move and have their being.

We should like to conclude our remarks by emphasizing this aspect of the subject, as it is one that can be appreciated and acted upon by local communities and even individuals.

We have mentioned a number of examples of beaches being ruined by the carelessness of human beings, who have built fine walls to support the water-front promenades that once were the carriage-drives of elegant society and now are packed with cars and summer visitors out for their evening stroll.

These magnificent but ill-advised undertakings are in many cases the reason why the sandy beach which separates them from the low-water mark may subside or vanish altogether; a force proportionate to the square of the amplitude of the swell in the open ocean and to its length, which is about thirty times as great, beats against this thin layer of sand, so favoured as a place of recreation, and it becomes either a mass of jagged rocks with pools here and there, or a wet bank of clay.

No longer can the city visitor relax there and benefit from the healthful effects of the sea air and its iodine content.

It is the visitors who flock to the more popular beaches who are partly responsible for the deterioration of these areas, since the physical balance of natural formations is delicate and may easily be upset; for the constant tramping of feet has the same effect as a long series of storms. Just as people walking in Hyde Park or the Bois de Boulogne are asked to keep off the grass where

it has been re-planted, so the 'manager' of a beach should ensure the protection of the natural asset entrusted to him.

It is instructive to see how carefully the Dutch look after the protective armour of their sea coast and the turf growing on the lower slopes of the sand-hills facing the sea; for this purpose they even use sheep to keep the ground firm and to crop the grass. If children are allowed to slide down these slopes, they inevitably destroy the surface and leave it vulnerable to weathering and erosion; little children can easily wear down an opening through which the sea can attack at the lower levels. At Berck and west of Odet (Finistère), in France, several instances of deterioration of this sort have been observed.

Nowadays town councils sometimes use bulldozers to refill beaches on which storms have left pools and ridges. Recently, at Sainte-Adresse, we saw beach attendants re-shaping and raking together the little ledges of pebbles, with as much care as if they had been dealing with priceless treasures.

Spur dikes, coastal protective walls, the provision of sloping sections at the bottom of steep walls—these are measures which may, no doubt, counteract the overwhelming force of the sea or the more avoidable carelessness of man; but they are effective only to a certain extent, and they are always costly.

Even then the plans for such measures have to be co-ordinated, the work of construction speeded up, and a maintenance scheme adopted; the latter, particularly, is too often neglected by local communities who regard such structures as being of only minor importance and are unwilling to combine with their neighbours in order to employ responsible and experienced maintenance services backed by sufficient material and financial resources.

If it is decided to risk constructing a road which runs along the coast or encroaches on the ocean, the precaution should at least be taken of building it on cantilever supports or on piles sufficiently widely spaced to allow the waves to wash in as freely as before without premature breaking or obstruction. An incidental advantage is that such structures may shade the beach below from the midday sun. We are reminded of those beaches, only too rare along the Mediterranean coast, which have beautiful umbrella pines along the sea front—a welcome feature for those who fear the effect of too strong a sun. But this is a privilege that can only be enjoyed where there is no tide.

Two other dangers should be mentioned—first, that of excessively heavy building along the coastline thus forming a solid wall on a level with the offshore bar, with the consequent risk of scouring at the base of the wall. If such buildings are situated on top of the dunes, their weight may break down the sand foundations, the rubbish that accumulates round them may set up processes of decay and the undermining action of the sea will be facilitated. An example of this can be seen on the French coasts, where the sea is gradually getting the better of the defensive structures of the famous Atlantic Wall.

The second danger, which is more closely related to oceanography, is the gradual rise in the general level of the sea (approximately 0.07 metres since the

beginning of the century), no doubt as a result of the melting of the polar ice-caps. This swelling of the waves, which accentuates erosive action along the coast, together with the fact that (as a rough statistical table recently drawn up from the available data would seem to indicate) strong sea winds have been much more frequent, may well explain why coastal areas have been subjected to heavier onslaughts from the sea over the last thirty years or so.

Here, then, are a number of phenomena which provide Unesco with an opportunity to extend its useful work by calling the attention of States which are not sufficiently concerned with these problems, or which have not as yet passed laws affording real and effective protection, to the dangers which threaten the seasonal resorts and the curative and recreational facilities of their people who, at times of stress and fatigue seek relaxation on the shores of the ocean, whence all life is thought to have come.

## The proceedings of the International Conference on Information Processing

which was held at Unesco House from 15 to 20 June 1959 will be published in April 1960. This volume will include: a general introduction, the full text (in English or French) of the 61 papers discussed during plenary sessions, an abstract of each paper in English, French, German, Russian and Spanish, introductory and summary reports of the discussions in English or French, summaries of the 65 communications delivered during the 12 symposia held during the conference, and a general report on the conference in English and French. This cloth-bound volume, published jointly by Unesco (Paris), Oldenbourg Verlag (Munich) and Butterworth Scientific Publications (London) will consist of 600 pages, printed in letterpress. Its format will be 21 × 29.7 cm (8 1/4″ × 1 1/4″). The price will be $25; £7.7.0 (stg.); 100 NF; 84 DM. Copies may be obtained from the Unesco Bookshop and from national distributors of Unesco publications (see list at the end of this issue).